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INFORMAL REPORT

A VOLUME SCATTERING AND OCEANOGRAPHIC STUDY OF AN AREA IN THE EASTERN GULF OF MEXICO

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INFORMAL REPORT

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ABSTRACT

Volume reverberation data from the deep scattering layer and oceanographic data for June 1966 are presented for an area located in the Gulf of Mexico. Volume scattering strength values are presented for one-third octave bands between 2.5 kHz and 20 kHz. Values of scattering strengths range from a minimum of -69 dB at 2.5 kHz to a maximum of -48 dB at 5 kHz. Diurnal variations of scattering strength with frequency are shown; the values decreasing with increasing frequency. Echo sounder records of scattering layers resonant at 12 kHz are examined for one station and the apparent migration rates and layer thicknesses discussed.

Oceanographic data, collected coincident with the acoustic data, indicate that the area under investigation is located within Florida Current water. Historical oceanographic data shows that water lying off the west coast of Florida forms a boundary with the Florida Current Water and that this boundary zone can be expected to approach or transverse the area occasionally. Both the collected acoustic and oceanographic data show little variation from location to location.

This report has been reviewed and is approved for release as an UNCLASSIFIED Informal Report.

APPROVED FOR RELEASE: M. U. Burkhard
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INTRODUCTION

This report presents the preliminary results of scattering layer investigations in a small area, known as Area LIMA, located in the Gulf of Mexico (Figure 1). The boundaries of the area under study are from latitude 24°00' to 26°00'N and from longitude 85°00' to 86°30'W. Water depth averaged 3300 meters.

The deep scattering layer, as observed in most of the world's oceans, has become the object of intensive research and speculation. The presence of the deep scattering layer generally is shown by a "thickening" of midwater echoes on an echo sounder record. Net hauls and biological research on marine organisms indicate that the organisms which inhabit the depths of the deep scattering layer are primarily responsible for reverberation from the ocean volume. Further, it appears that the organisms which possess swim bladders are the primary agents responsible for sound scattering (Marshall, 1951).

Volume reverberation refers to sound scattered back towards the receiver from inhomogeneities in the oceanic medium. Although turbulence and thermal microstructure may contribute slightly, the primary causative inhomogeneity is thought to be swim bladders of fish. Acoustic theory of bubbles shows that the result of insonification of the swim bladder (treated as a bubble) is to force the bubble into resonant oscillation at a frequency whose wavelength is much larger than the diameter of the bubble. Hence, explosive sound sources are used because they contain many frequencies, are of short pulse length, and high intensity.

Biological tows were made at depths above the layer during daylight hours and within the layers at night. To obtain maximum simultaneity, tows were conducted before and after each acoustic sequence using a Be' multiple plankton sampler. Depths for towing were determined primarily by examination of the echo sounder records. Net catches were preserved for subsequent sorting and identification ashore.

Temperature, salinity, phosphate, and silicate data were obtained in conjunction with the acoustic and biological data gathering program. The collected hydrographic data have been augmented by data collected by research programs conducted in the general area. These hydrographic data have been combined to show the physical characteristics of the water column during the reported cruise, the variability of these characteristics with time, and the horizontal variation of the physical characteristics of the water of Area LIMA and the adjacent area to the northeast.

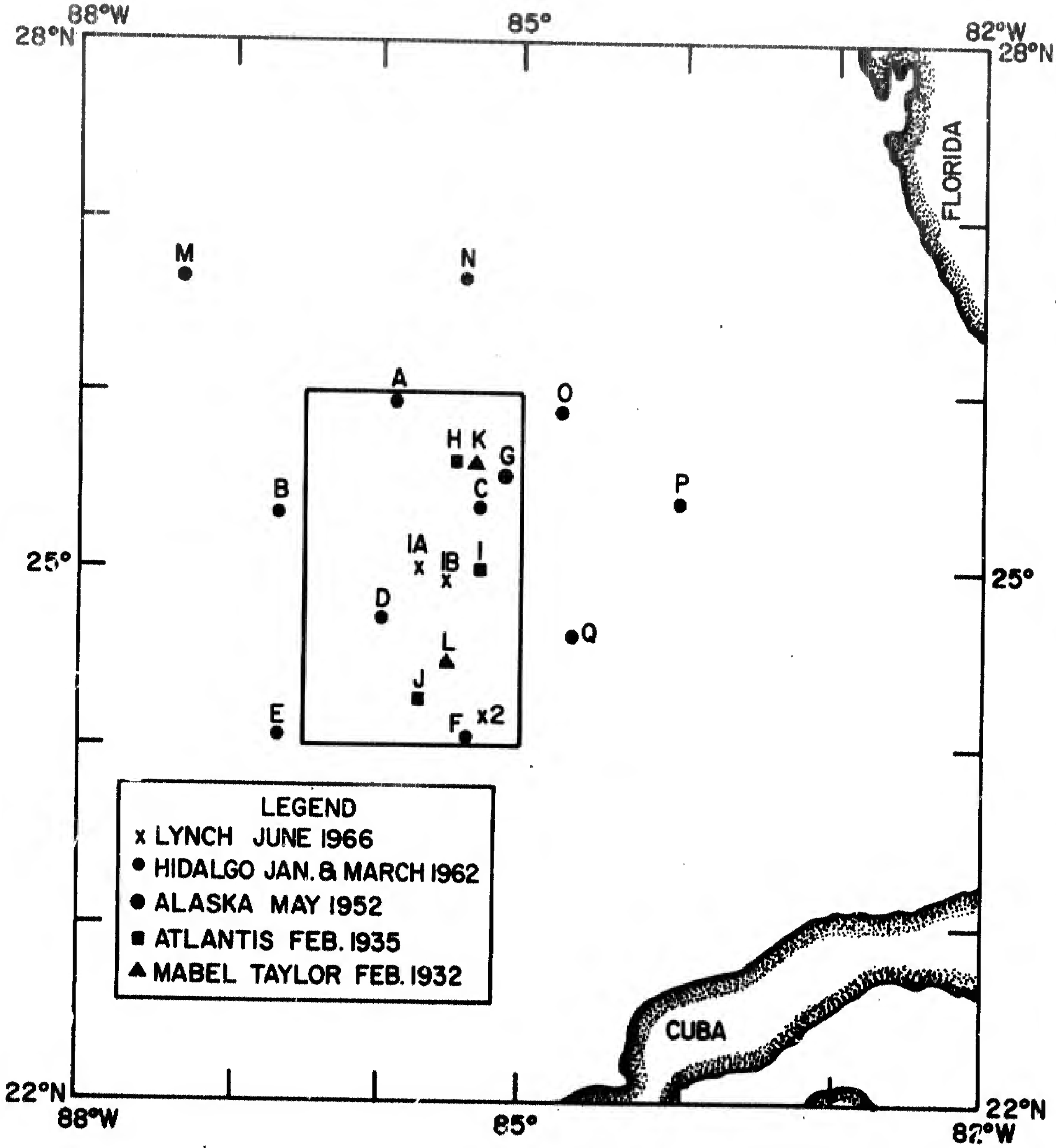

FIGURE 1. AREA AND STATION LOCATION

ACOUSTICS

Considering individual scutterers, we may define the back-scattering coefficient m_v as the power that would be scattered by a unit volume of ocean per unit intensity of incident plane wave, if the scattering in all directions is equal. The unit volume of ocean is defined as one cubic meter.

Expressed in logarithmic form

$$10 \log m_v = 10 \log \frac{4 \pi I_s}{I_i \Delta V} \tag{1}$$

where

I_s = intensity of the scattered sound,

I_i = intensity of the inciuent sound, and

ΔV = unit volume of ocean.

This back scattering coefficient has units of db/ m and is analogous to a back scattering coefficient defined by $N \sigma$.

Classically an object which is able to reflect or reradiate sound can be expressed by a target strength defined as follows:

$$\text{Target Strength} = 20 \log \frac{Ps}{Pi} \tag{2}$$

where

Ps = pressure amplitude of scattered sound measured at a reference distance of one yard, and

Pi = pressure amplitude of incident sound.

It then follows that the target strength (scattering strength per unit volume) can be expressed by $10 \log \frac{m_v}{4\pi}$ (Urick and Pryce, 1954).

The volume scattering strengths presented in this report were obtained using the scattering strength equation presented by Gold (1966) and derived in Appendix A.

$$10 \log \int_0^z M(z)\, dz = 20 \log P(t) + 30 \log T$$

$$-10 \log \tan^{-1} \left[\frac{2 \pi \alpha (f_2 - f_1)}{1 + 4 \pi^2 \alpha 2 f_2 f_1} \right] \quad -86 \qquad (3)$$

Equation 3 is referred to as scattering strength because the equation has a form similar to that of the equation for surface backscattering strength (Chapman and Harris, 1962).

The term $10 \log \int_0^z M(z)\, dz$ represents the total scattering strength for a water column with a $1 m^2$ cross section extending from the surface to a depth z.

EXPERIMENTAL TECHNIQUES

Eight series of volume reverberation measurements were made at two stations within the area during June 1966, aboard the USNS LYNCH (T-AGOR-7), to determine scattering strengths of the deep scattering layer.

The experimental geometry is illustrated in Figure 2. An LC-32 omnidirectional hydrophone was lowered over the windward side of the ship to a depth of approximately 107 meters. Mark 50 Mod 0 charges (2 lbs. TNT) were detonated at a preset depth of 107 meters, at the rate of one explosive every 8 minutes, for full daylight and full nighttime measurements and every 6 minutes for sunrise and sunset sequences. The deep scattering layer was insonified by the resultant shock wave, setting the swim bladders of fauna present into forced vibration. The received reverberation is amplified and filtered through a 500 cycle high-pass filter and recorded on magnetic tape. The magnetic tapes were played through a one-third octave band analyzer and displayed on a logarithmic oscillographic recorder. Since bubble pulses and surface reverberation contribute to the reverberation levels for a short period of time only, (negligibly after approximately .4 sec.), values of P(t) are read at 0.5, 1.0, and 1.5 seconds after the onset of reverberation and the average value used. This has the effect of summing the contributions from all the scatterers present in the water column. Scattering strengths were then computed by use of equation 3.

Concurrently with the explosive acoustic sequence, supplementary 12 kHz reverberation data were obtained using the ship's Edo UQN-1 echo sounder transducer, Gifft transceiver, and Precision Depth Recorder. Echograms were recorded continuously, except during the explosive reverberation

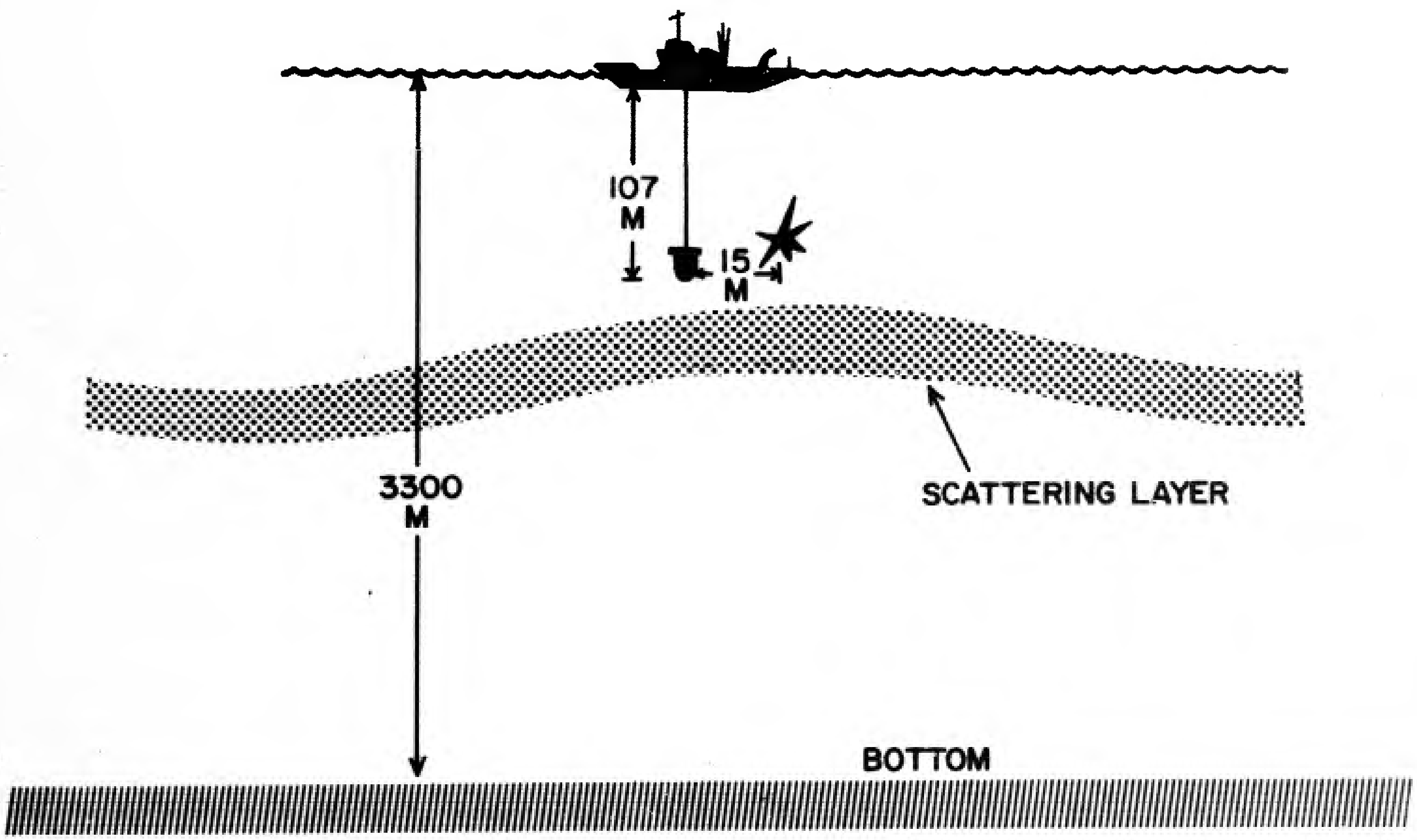

FIGURE 2. SCATTERING STRENGTH MEASUREMENT GEOMETRY

measurements, yielding qualitative data on the deep scattering layers. Acoustic sequences were conducted under quiet ship conditions. Wind speed averaged about 6 knots and sea heights about 2 meters.

ACOUSTIC RESULTS

Figures 3 and 4 present graphs of scattering strength versus frequency for Stations 1 and 2, for full day and full night conditions respectively. The graphs are very similar at Stations 1 and 2. Both curves show a definite positive increase up to 5 kHz. The "peaks" in the scattering strength-frequency curves appear to indicate the presence of more than one layer. The "peaks" are significant (less than ±.5 db standard deviation for an average of 10 bomb shots) and from the second peak at 16.0 kHz, which occurs at night and day, one may infer that one layer may be non-migratory in nature. Nighttime values are generally higher than daytime values owing to the increased concentration of scatterers at night. The increase averaged about 7 db for Station 1 and 3 db for Station 2 for the entire frequency range investigated.

Layer migrations across sunset and sunrise at 5 kHz for both stations are shown in Figures 5 through 8. The curves show scattering strength plotted as a function of time for a three hour period centered about local sunrise or sunset. The 1/3 octave filter centered at 5 kHz was used because the maximum scattering strength values observed usually occurred in this region.

Figure 9 shows the diurnal variation of scattering strength for each of the one-third octaves investigated. Diurnal variation is defined as the difference in decibels between the maximum nighttime and minimum daytime values. It is not understood why the maximum diurnal variation differs for the two stations. The greatest variation occurs at 3.2 kHz for Station 1 (12 db) and at 4.0 - 5.0 kHz for Station 2 (7 db). The dissimilarity in the magnitude of the curves for the two stations can be explained by reference to Figures 3 and 4. For full day conditions the scattering strengths at Station 2 are higher, while for full night Station 1 has the greater values.

Figure 10 shows the peak or maximum resonant frequency of the scattering layer, or layers, as it changes during migration at Station 1. This figure shows a daytime resonant peak of 16 kHz and a nighttime resonant peak of 5 kHz. The scattering of points around sunrise is probably due to a multi-layering effect. Multi-layering refers to two or more distinct layers, or one layer, which divides at sunset and then recombines after sunrise. Such a multi-layer could contain different kinds of scatterers, each of which has its own characteristic resonant frequency. This could account for the "flatness" of the full day and full night curves between 5 kHz and 12 kHz in Figures 3 and 4.

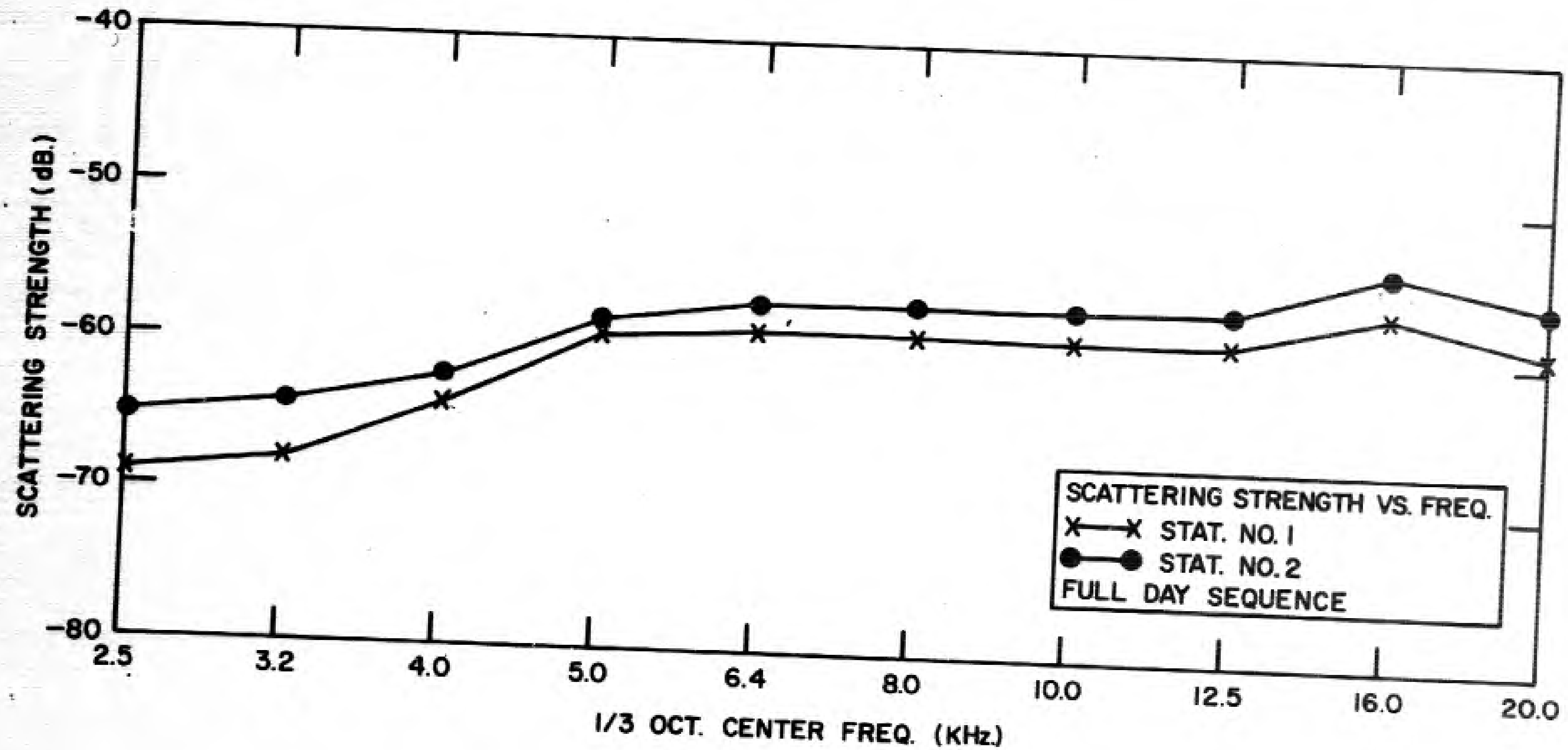

FIGURE 3. DAYTIME SCATTERING STRENGTH, STATIONS NO. 1 AND 2

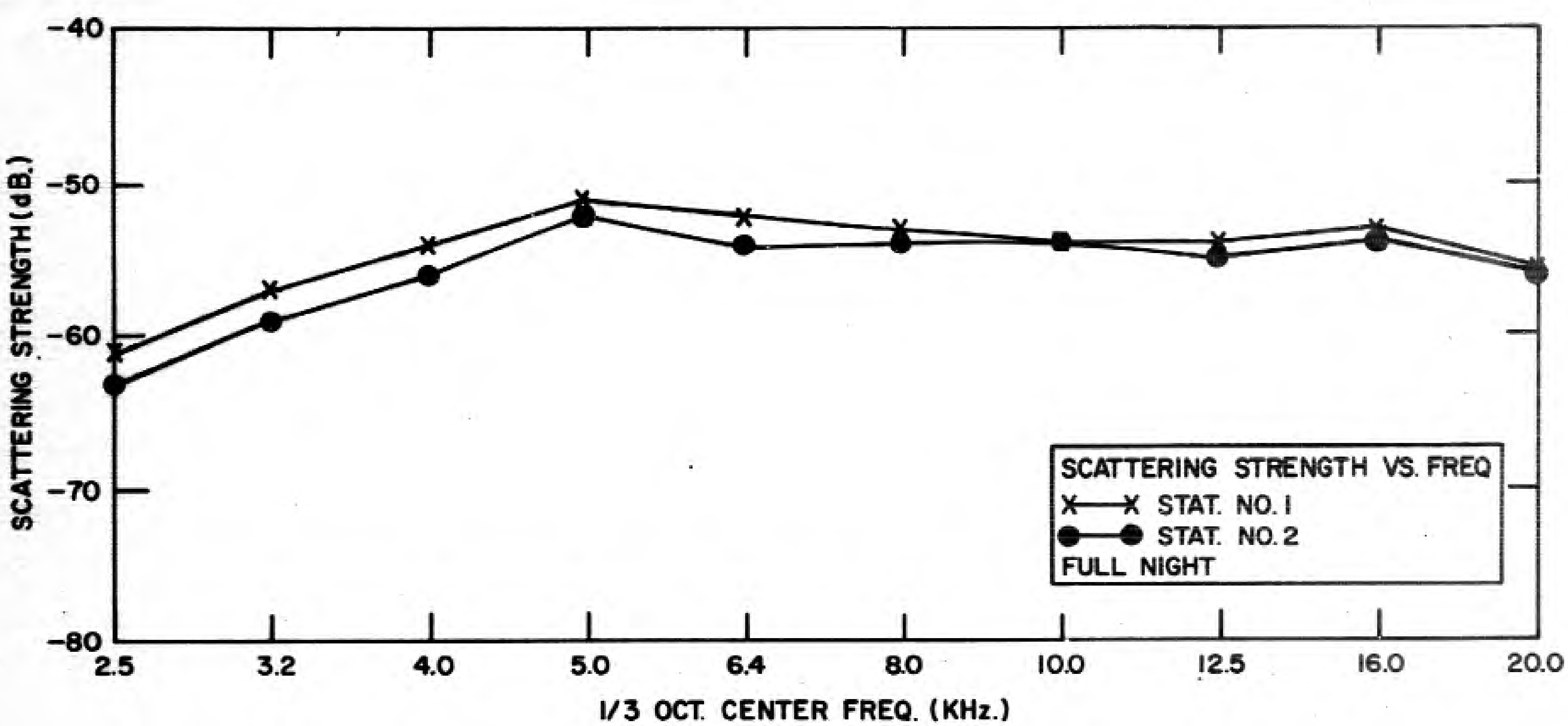

FIGURE 4. NIGHTTIME SCATTERING STRENGTH, STATIONS NO. 1 AND 2

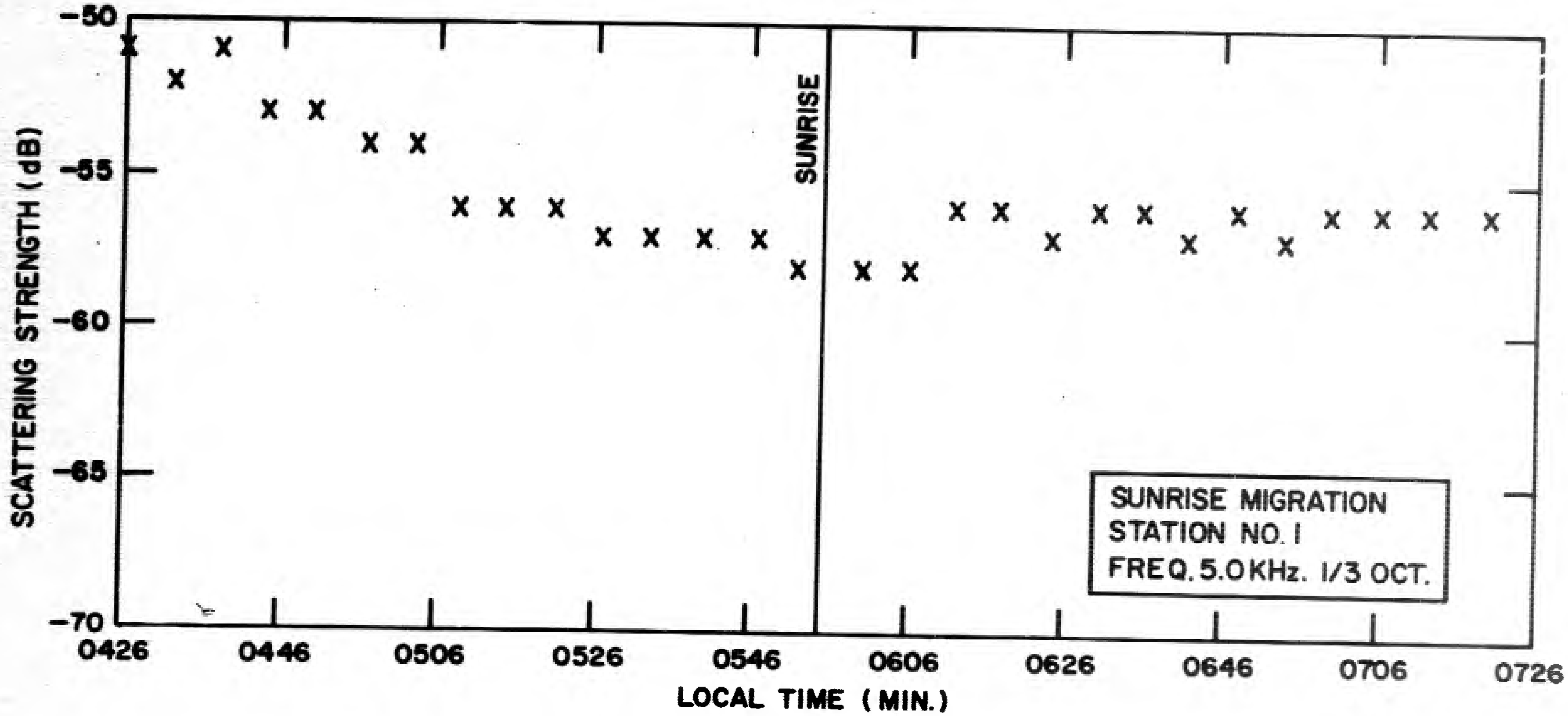

FIGURE 5. SUNRISE MIGRATION, STATION NO. 1

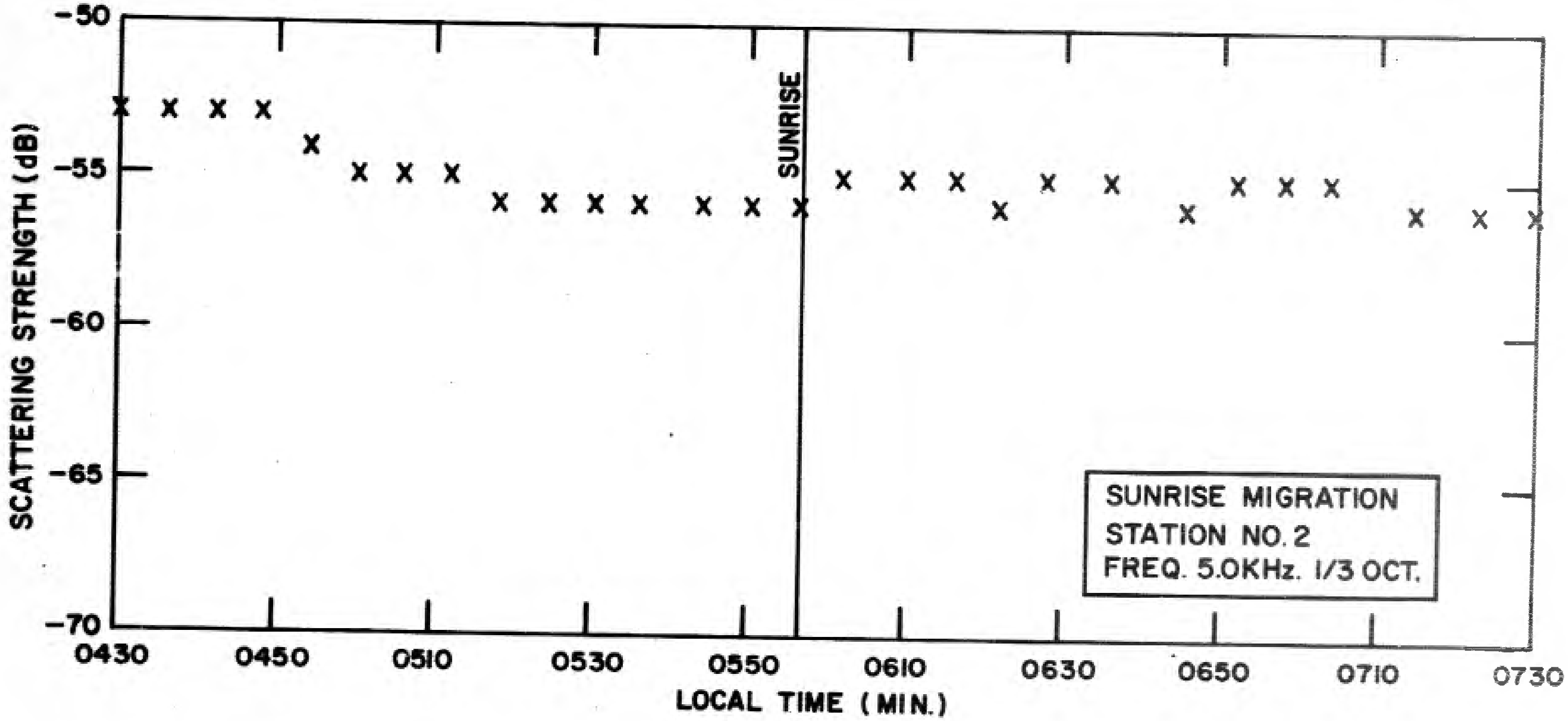

FIGURE 6. SUNRISE MIGRATION, STATION NO. 2

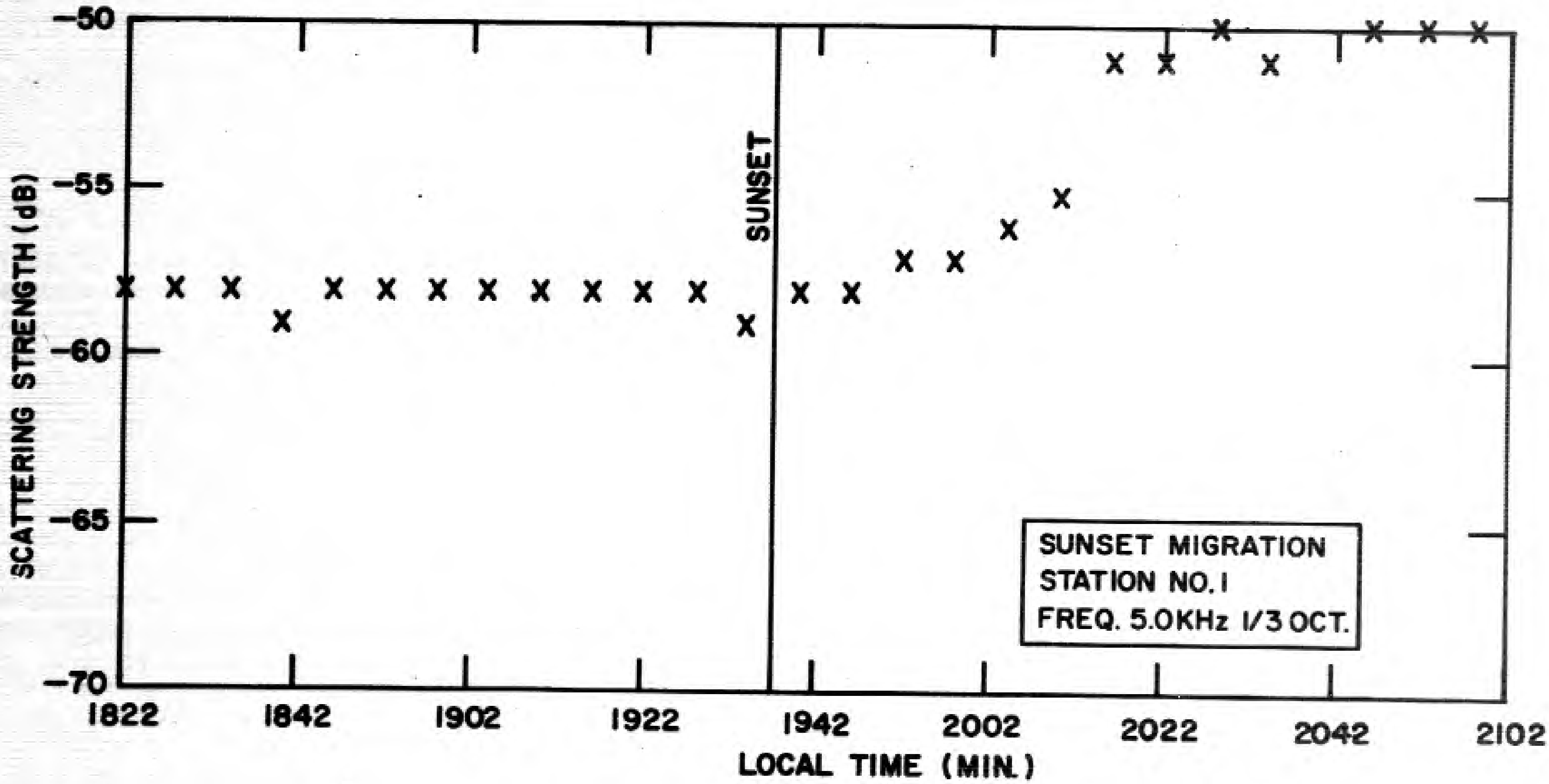

FIGURE 7. SUNSET MIGRATION, STATION NO. 1

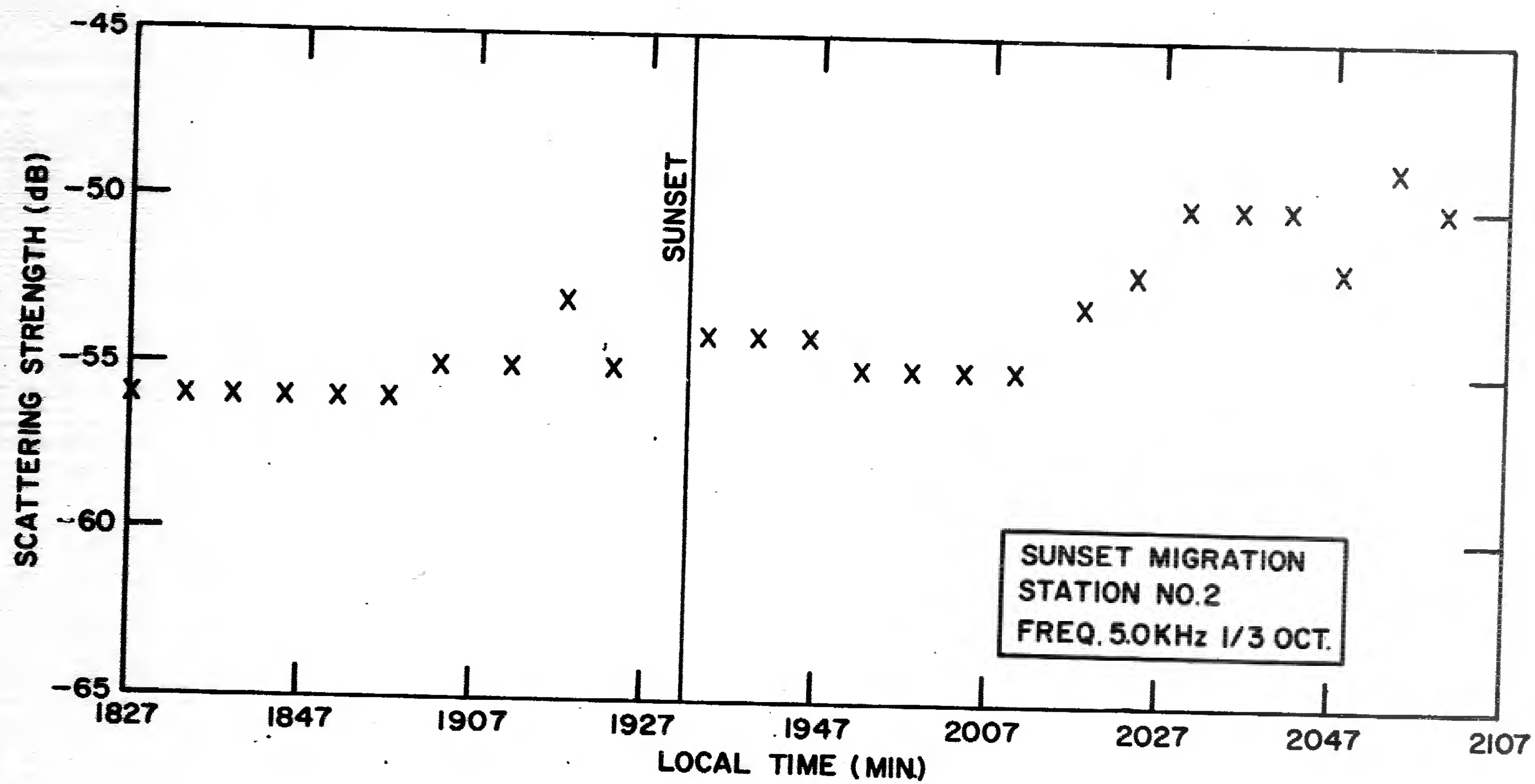

FIGURE 8. SUNSET MIGRATION, STATION NO. 2

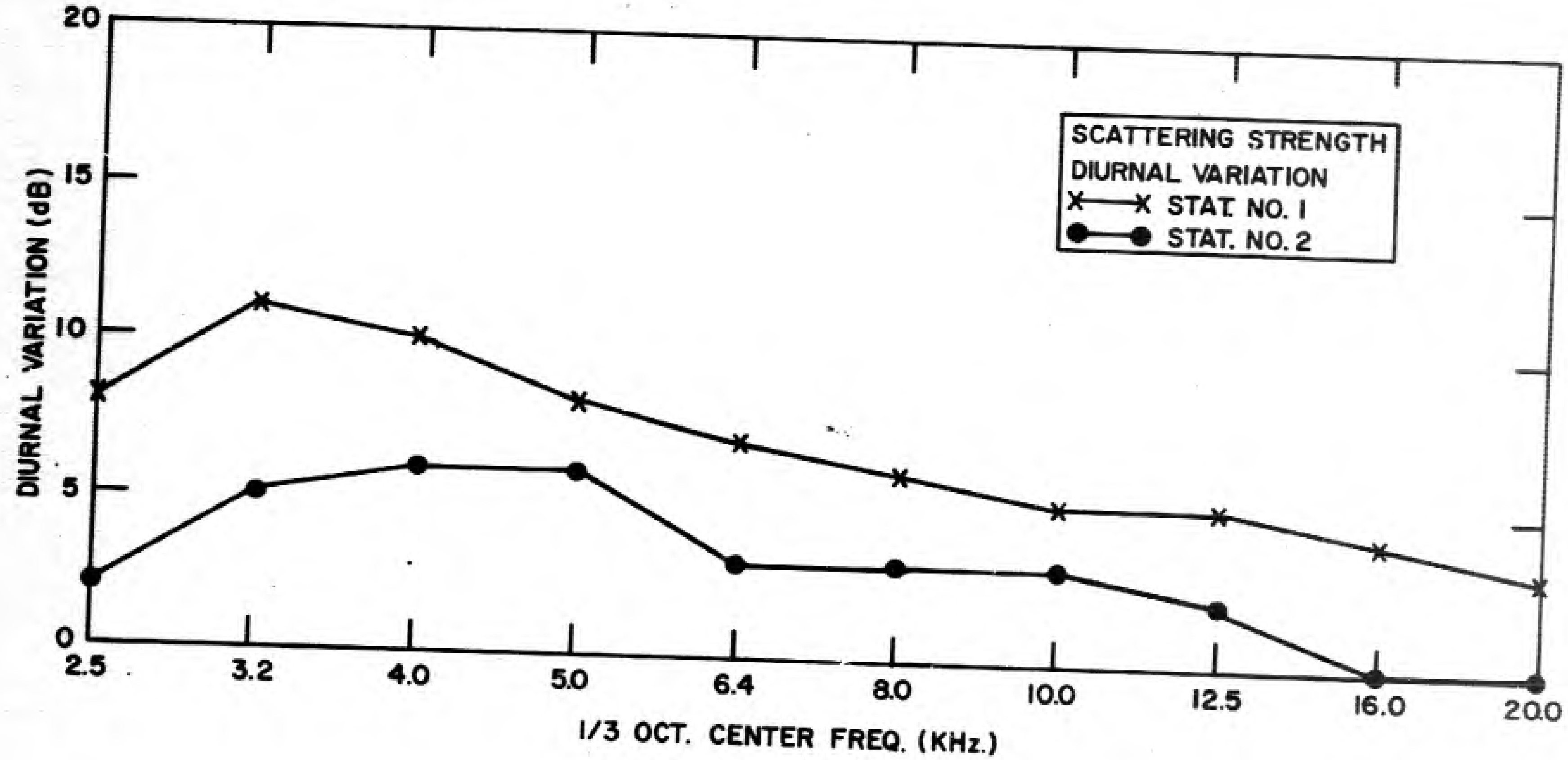

FIGURE 9. DIURNAL VARIATION OF SCATTERING STRENGTH, STATIONS NO. 1 AND 2

Migration rates are not shown accurately by Figure 10. In order to determine migration rates, echograms obtained during the occupation of Station 1 were examined. Four layers were observed, three of which were prominent at all times and one which was evident during migrations only. The shallowest layer was readily discernible throughout the duration of Station 1. It did not appear to undergo migration at either sunset or sunrise, but remained constant at a depth of approximately 100 m. Its apparent thickness averaged about 35 meters. A second layer appeared prominently before sunset, migrated upwards, and after sunset appeared rather continuously until sunrise. This layer occupied the depths between 140 and 160 m before migration. A vague third layer, at about 250 m, appeared just before sunset, exhibited migration over the sunset period, and finally merged with the uppermost layers. Its density was very sparse and nothing definite can be said about its nature. The last layer observed was notable because most of the observed migration was due to this layer, which showed pronounced upward movement at sunset and an equal downward movement at sunrise. The migration rate computed from the record was about 11 m/min. The recorder was operated on a 733 meter (400 fathoms) sweep rate and since the bottom was at 3300 meters, scattering layer information below a depth of 360 meters was obscured by the bottom trace. During upward migration at sunset, the four layers were observed to merge into one diffuse mass which extended from the surface down to about 130 meters. The apparent thickness of the individual layers varied from as little as 50 meters to as much as 150 meters.

BIOLOGY

At the time of this writing, the sorting and identification of the marine organisms collected has not been completed. It is anticipated that the biological analyses will be completed before a second experiment, in the same area, which is scheduled for March 1967. These results then will be included in a summary report.

OCEANOGRAPHIC DATA COLLECTION METHODS

Temperature measurements were made using standard Nansen water bottles fitted with reversing thermometers. Temperature values collected by this method are accurate to ±.02°C (Sverdrup et al. 1942). Water samples collected by the Nansen bottles were analyzed for salinity, inorganic phosphate, and silicate concentrations. Salinity values were determined by salinometer on board ship and are characteristically accurate to ±.003 0/00 (Brown and Harmon, 1961). Water samples for phosphate and silicate determinations were stored frozen in polythylene bottles until they were processed

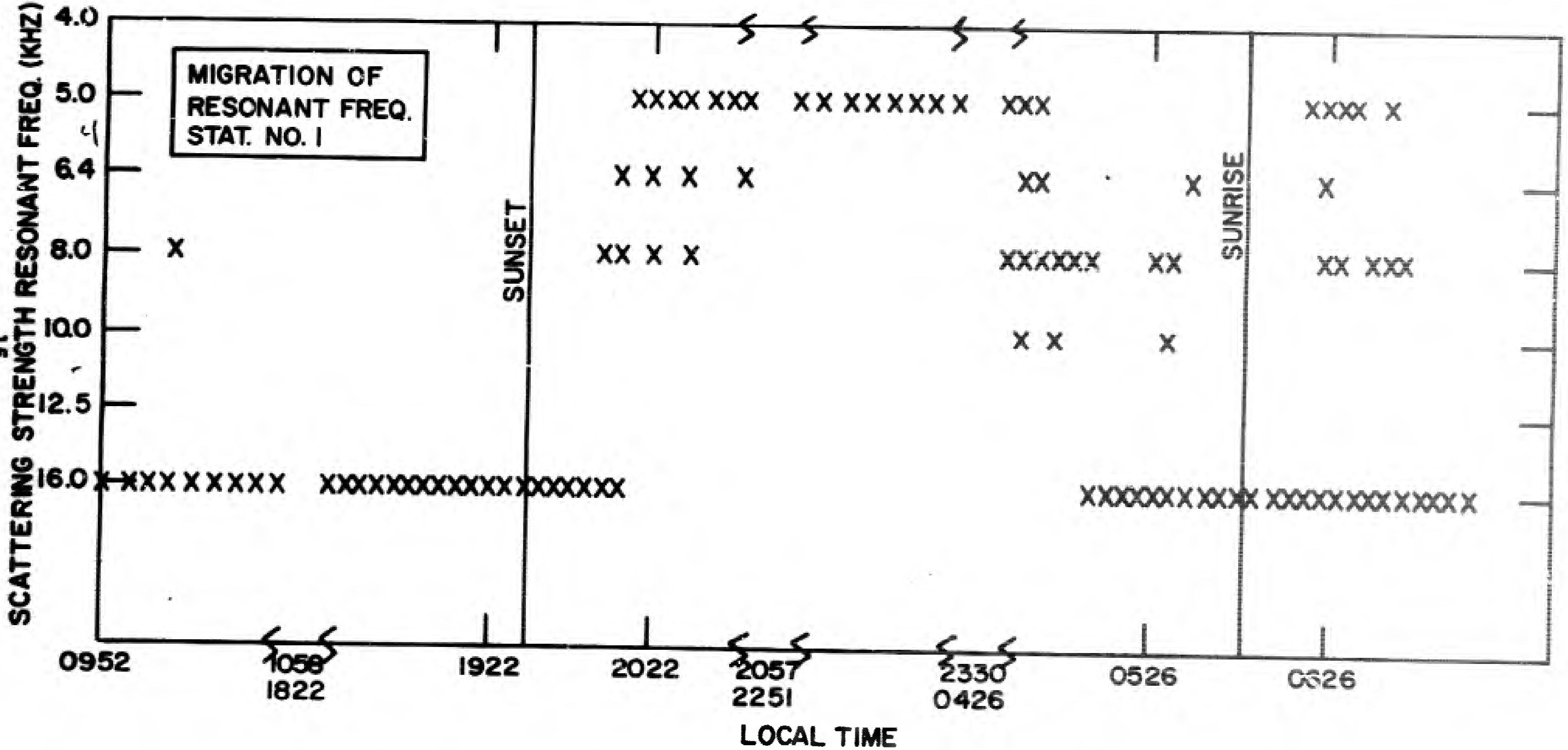

FIGURE 10. MIGRATION OF SCATTERING STRENGTH RESONANT FREQUENCY, STATION NO. 1

TABLE I

STATION LOCATION, DATE, AND TYPE OF DATA OBTAINED

STATION	TEMPER-ATURE	SALIN-ITY	OXY-GEN	PHOS-PHATE	SILI-CATE	DATE	LONGITUDE	LATITUDE	DEEPEST DEPTH (IN METERS)
1-A	X	X		X	X	6/22/66	85°45'W	25°00'N	500
1-B	X	X		X	X	6/22/66	85°38'W	24°54'N	2290
2	X	X		X	X	6/23/66	85°14"W	24°18'N	500
A	X	X	X	X		3/1/62	85°56'W	25°57'N	2841
B	X	X	X	X		3/1/62	86°41'W	25°19'N	2953
C	X	X	X	X		2/26/62	85°16'W	25°21'N	2018
D	X	X	X	X		2/25/62	86°00'W	24°44'N	2964
E	X	X	X	X		2/25/62	86°41'W	24°03'N	1092
F	X	X	X	X		2/24/62	85°18'W	24°03'N	2921
G	X	X				5/29/52	85°07'W	25°33'N	1183
H	X	X	X			2/22/35	85°26'W	25°36'N	1460
I	X	X	X			2/21/35	85°17'W	25°00'N	1450
J	X	X	X			2/18/35	85°44'W	24°15'N	2886
K	X	X				2/17/32	85°20'W	25°35'N	3200
L	X	X				2/16/32	85°30'W	24°27'N	3000
*M	X	X	X	X		3/3/62	87°20'W	26°39'N	2488
*N	X	X	X	X		3/1/62	85°23'W	26°39'N	3000
*O	X	X	X	X		2/26/62	84°48'W	25°54'N	953
*P	X	X	X	X		2/23/62	84°02'W	25°22'N	122
*Q	X	X	X	X		2/24/62	84°40'W	24°38'N	1382

SHIP'S NAME	STATION OCCUPIED
LYNCH	1-A, 1-B, 2
HIDALGO	A, B, C, D, E, F, M, N, O, P, Q
ALASKA	G
ATLANTIS	H, I, J
MABEL TAYLOR	K, L

*STATION OUTSIDE OF AREA LIMA USED ONLY TO DEFINE THE AREA OCCUPIED BY B WATER.

in the laboratory. Both phosphate and silicate samples were processed chromatographically as described by Murphy and Riley (1962) for phosphate, and Strickland and Parsons (1965) for silicate. Phosphate values are accurate to 0.01 μg-at/L and silicate values to 0.1 μg-at/L. BT data to a depth of approximately 900 feet (275 meters) were collected before and after each Nansen cast, acoustic sequence, and biological tow. Historical data (Table 1) were obtained from a data search conducted in the Oceanographic Office.

WATER CHARACTERISTICS

An examination of the temperature, salinity, and oxygen profiles (Figures 11, 12, and 13) indicates that the profiles fall into two groups. The present data (June 1966) and nine of the historical sets of data fall into one group. This group will hereafter be referred to as A water. The data from the three remaining stations fall into a second group hereafter referred to as B water.

In order to define the relative positions of A and B water with respect to each other and Area LIMA, temperature data collected in 1962 by the R.V. HIDALGO, in Area LIMA and the surrounding area, were plotted against depth to determine whether it was A or B water (Figure 14). A surface plot of these stations was then made to show the boundary between water of A and B character during the winter of 1962 (Figure 14). The approximate location of surface currents for the Gulf of Mexico, as depicted by Leiper (1954), is shown by Figure 15. Comparison of this current chart with the relative position of A and B water indicates that B water is almost certainly associated with a large gyre of water off the west coast of Florida and A water with the Florida Current, which brings in water from the Caribbean. The gyre off the Florida Coast probably represents a much shallower current than the Florida Current, since much of the course of the gyre lies over the shallow continental shelf west of Florida.

The two bodies of water differ mainly in the temperature characteristics of the seasonal thermocline, the depth of their respective permanent thermoclines and haloclines, and the depth at which the oxygen minimum occurs. In A water, the bottom of the seasonal thermocline is marked by a sharp inflection in the temperature profile (Figures 11, 14, and 16). In B water, this inflection is often absent and when it is present it occurs at a much shallower depth (Figure 11 and 14). The inflection point is only present in B water that is bordering on A water. During the winter months, A water develops an isothermal surface layer to a depth of between 100 and 150 meters (Figures 11 and 14). In B water, a comparable isothermal layer is either not

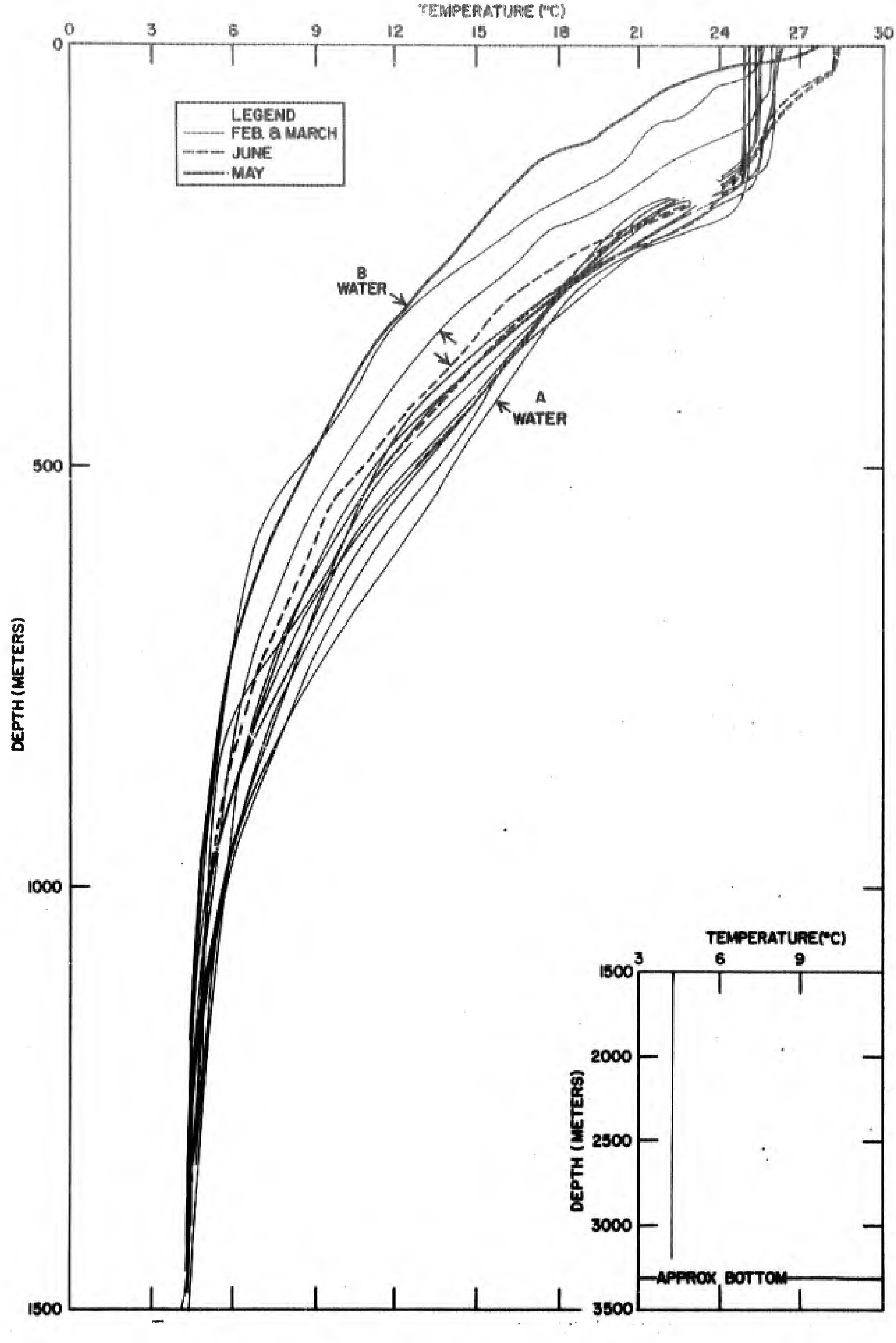

FIGURE 11. COMPOSITE OF TEMPERATURE PROFILES FOR STATIONS IN AND ADJACENT TO AREA LIMA

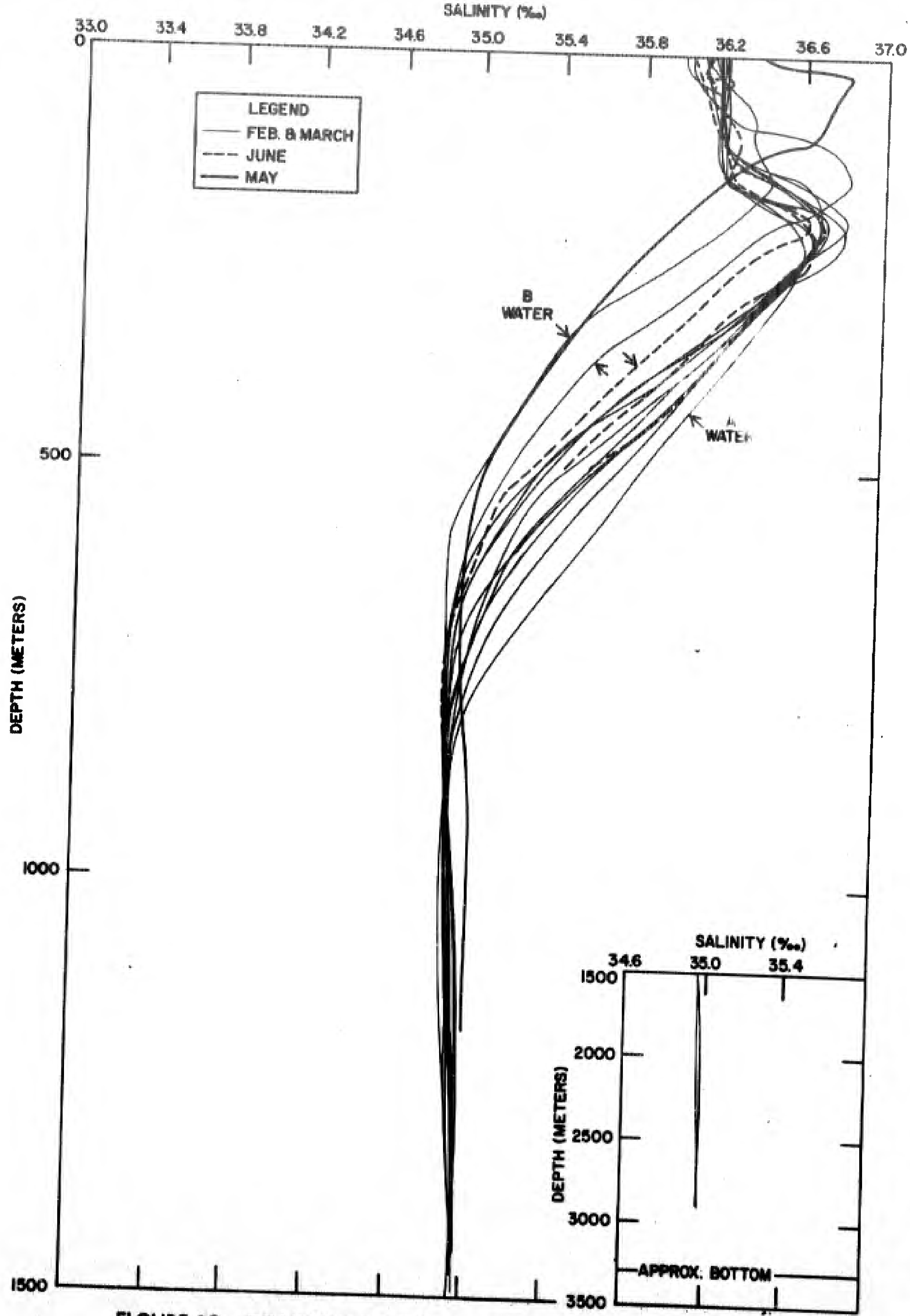

FIGURE 12. COMPOSITE OF SALINITY PROFILES FOR STATIONS IN AND ADJACENT TO AREA LIMA

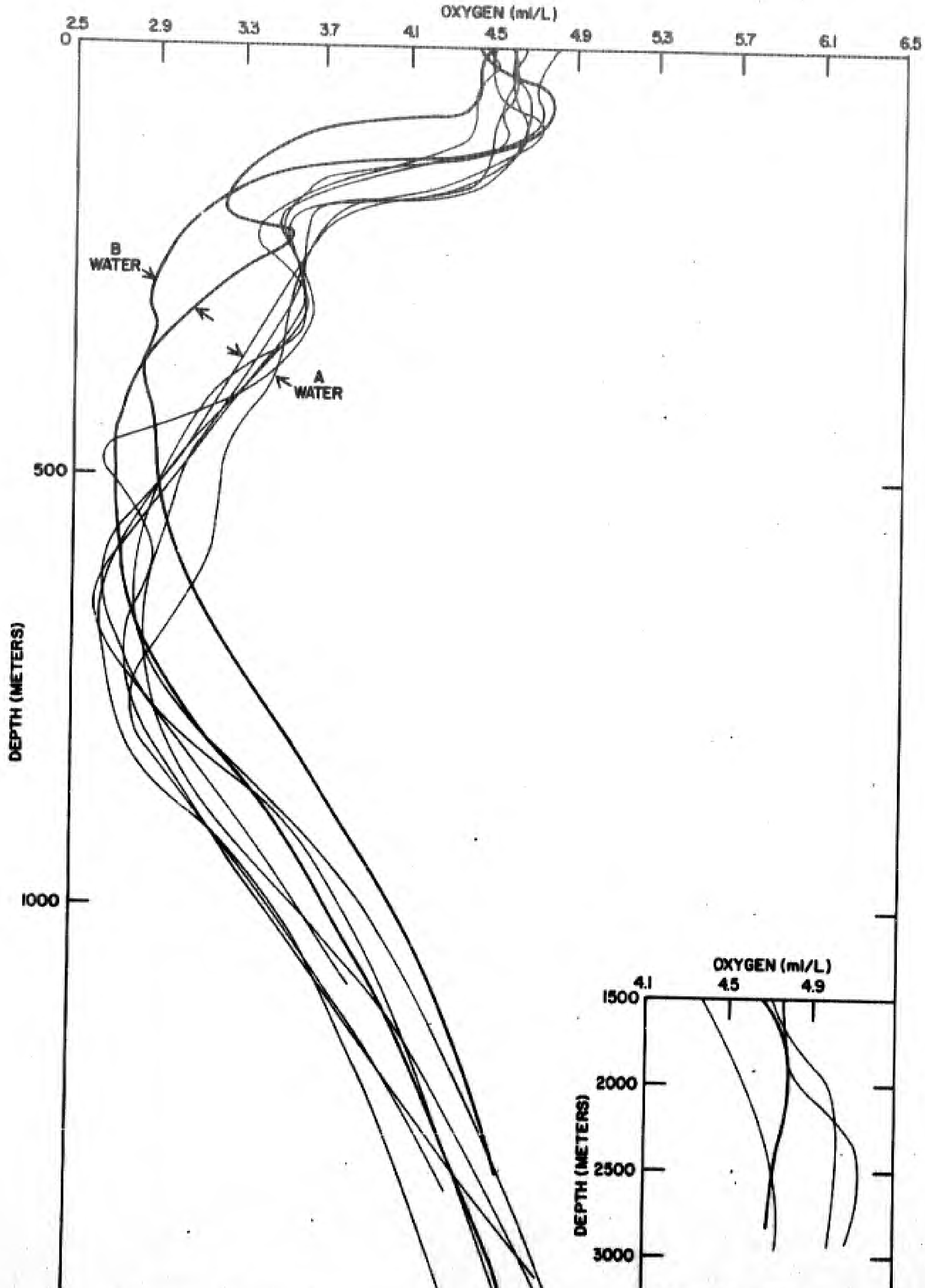

FIGURE 13. COMPOSITE OF OXYGEN PROFILES

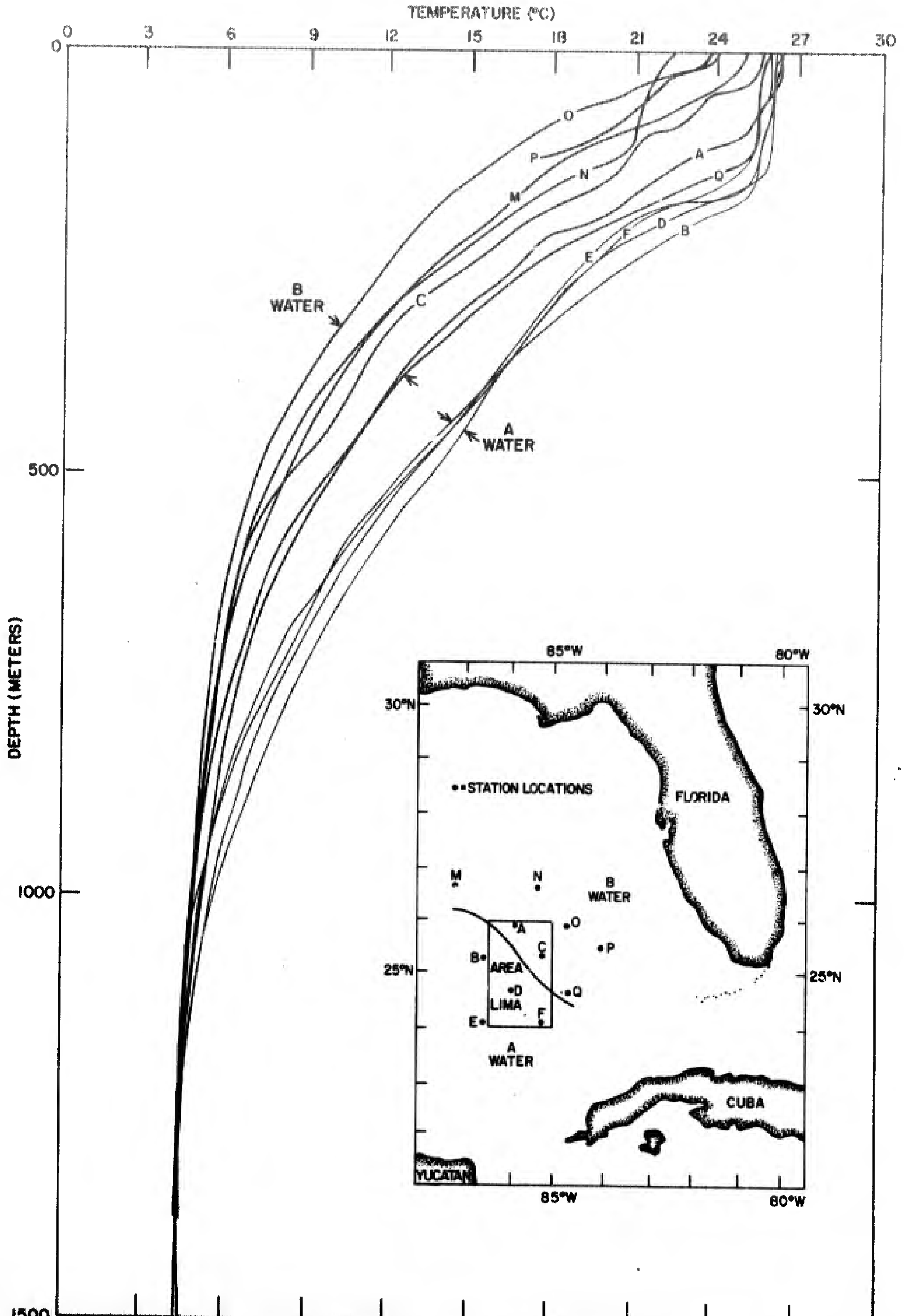

FIGURE 14. COMPOSITE OF TEMPERATURE PROFILES AND LOCATIONS FOR STATIONS OCCUPIED BY THE R.V. HIDALGO, 1962

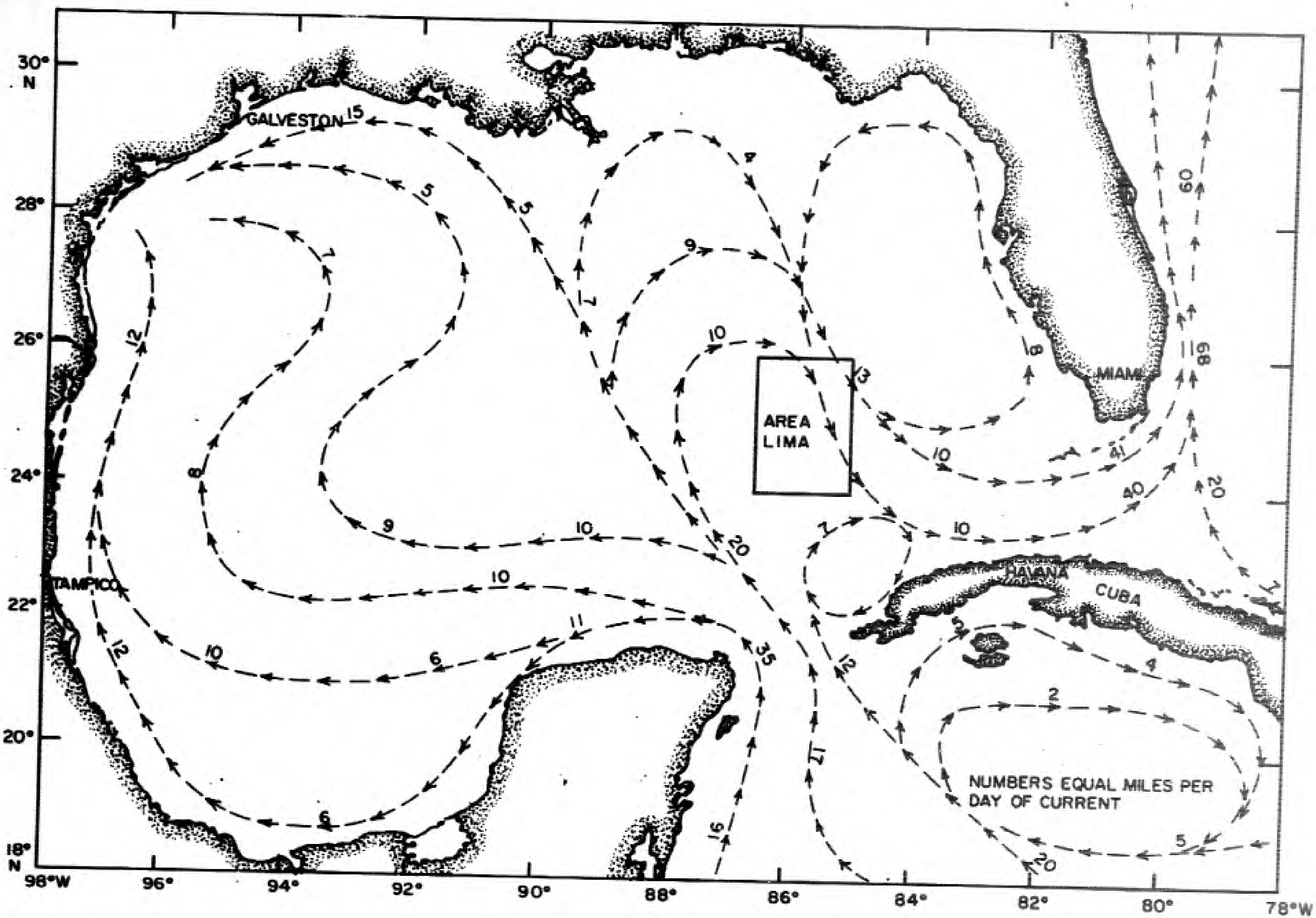

FIGURE 15. SURFACE CURRENTS IN THE GULF OF MEXICO DURING JUNE 1954

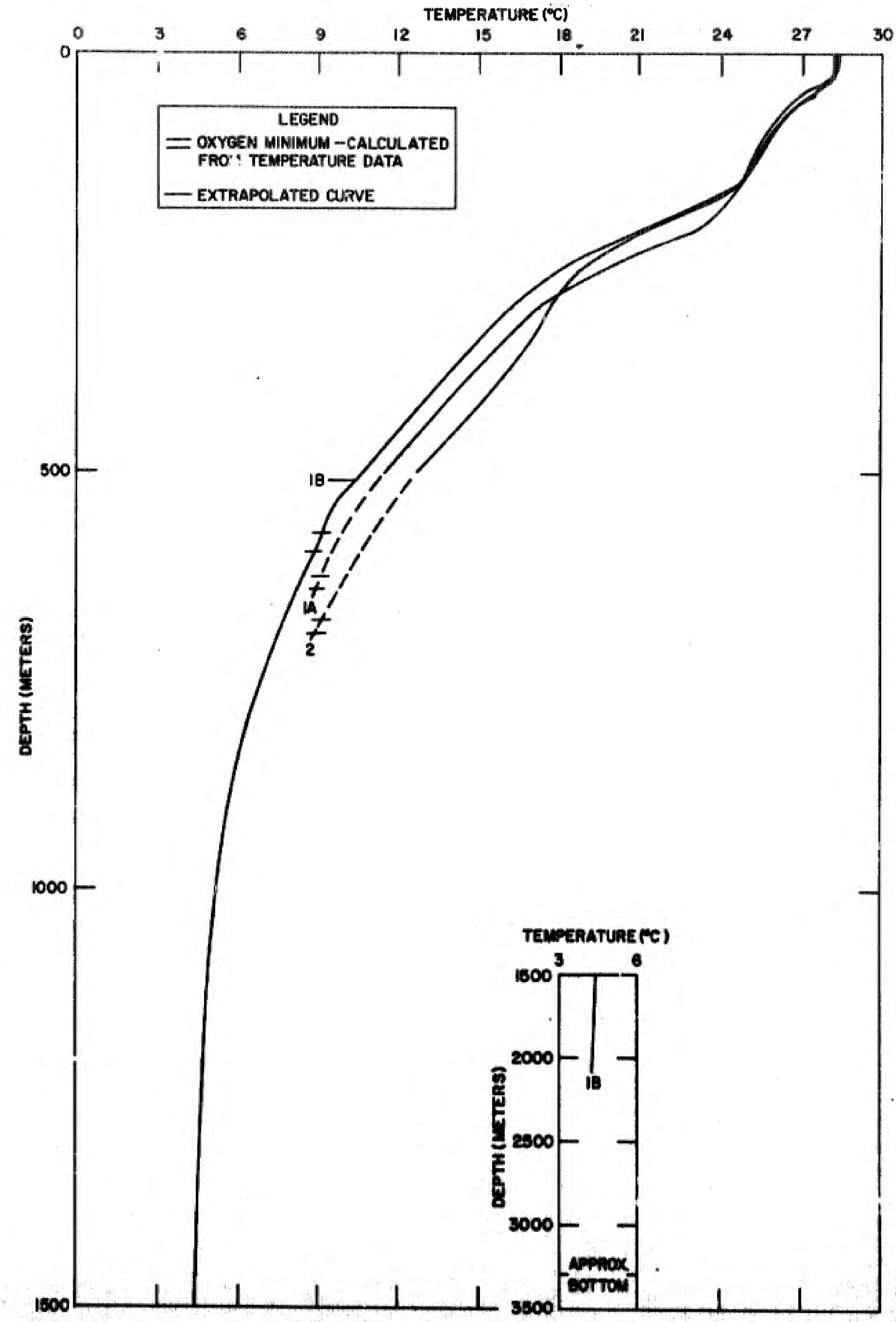

FIGURE 16. COMPOSITE OF TEMPERATURE PROFILES FOR JUNE 1966

developed or developed to a much shallower depth. This seems to indicate that B water suffers little winter cooling compared to A water. Conclusions, based on winter temperature profiles for B water, may be only apparent since the data represents only one winter (1962) and may not be true for other years. Below 150 meters, B water appears to have the same characteristics as A water but displaced upward in the water colum by approximately 200 meters. This applies to temperature (Figures 11 and 14), salinity (Figure 12), and the oxygen minimum (Figure 13).

TEMPERATURE

Characteristic of tropical waters, the temperature profiles from the present data show a warm body of water overlying a much larger body of cold water (Figure 11). At the time the data were collected, the seasonal thermocline was well developed. The bottom of the seasonal thermocline is indicated by a rather prominant inflection point at 150 meters (Figure 14). Temperature data collected in past years in and near Area LIMA indicate that at least for A water this inflection point does not vary a great deal in depth (Figure 11). The temperature data show that an isothermal layer existed at the time of the June 1966 cruise from the surface to 25 meters. The presence of this layer in June is due to mixing, either from wave action or surface cooling. During the colder months of the year, this isothermal layer can be expected to reach to the bottom of the seasonal thermocline (Figure 11).

The permanent thermocline is located between approximately 150 and 900 meters. As the name implies and Figure 11 indicates, seasonal temperature variations have no detectable effect on this layer. This layer shows considerable stability from 150 through 300 meters but somewhat greater variations from 300 to 900 meters. The temperature decreases approximately 19°C from the top to the bottom of the permanent thermocline. In Area LIMA, the 6°C isotherm approximates the bottom of this layer. Below 900 meters the temperature drops off slowly, reaching 4.2°C at approximately 1500 meters. From 1500 meters to the bottom, at approximately 3300 meters, the potential temperature of the water remains nearly constant.

SALINITY

In Area LIMA, the salinity values are approximately 2‰ greater at the surface than in the deep and bottom waters (Figures 12 and 17). Both the North and the South Atlantic display the same feature in the lower latitudes.

During June 1966, a well developed seasonal halocline was observed (Figure 17). This halocline correlates with the seasonal thermocline discussed previously. A comparison of seasonal salinity data at these depths (Figure 12)

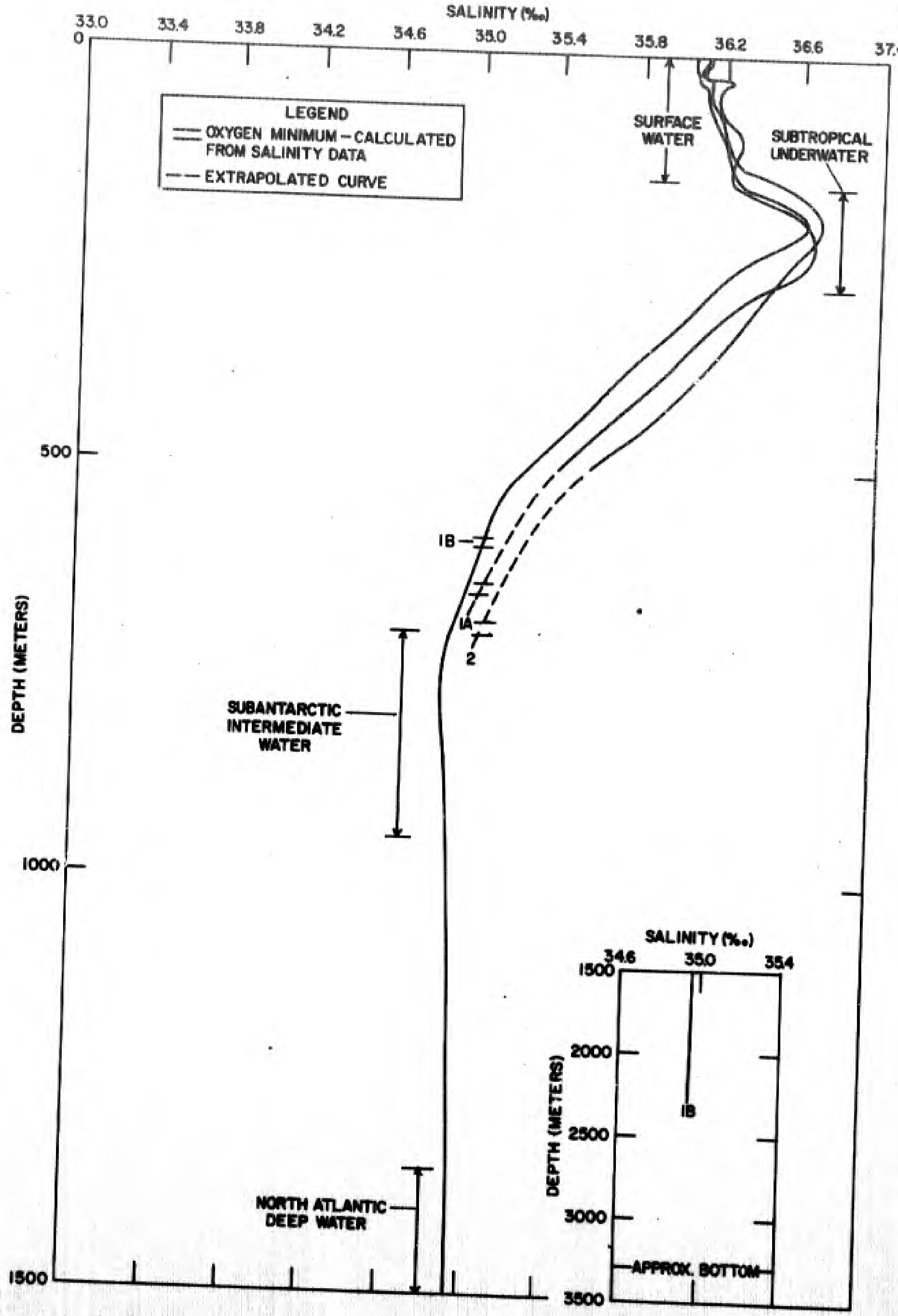

FIGURE 17. COMPOSITE OF SALINITY PROFILES FOR JUNE 1966

indicates that salinity values decrease during the warmer months of the year. During the cooler months of the year, overturning of the surface water to a depth of between 100 and 150 meters destroys both the seasonal halocline and thermocline. This causes an isohaline condition to exist during the winter months (Figure 12).

Directly below the seasonal thermocline exists a well developed salinity maximum. The core of this maximum approximates the 200 meter depth in A water and is found at a somewhat shallower depth in B water. This maximum represents the core of Subtropical Underwater which will be discussed later. The permanent halocline is found from approximately 200 to 700 meters. Unlike the seasonal halocline, its salinity values decrease as the depth increases. It is between approximately the 200 and 500 meter depth that salinity values show their greatest variations (Figure 12). At the termination depth of the permanent halocline, there exists a slight salinity minimum. This minimum represents Subantarctic Intermediate Water, about which more will be said later. This minimum ranges in depth from about 600 to 1000 meters but averages approximately 800 meters (Figure 12). Salinity minimums of this water type above 750 meters represent B water. Below 1300 meters the water is essentially isohaline. Salinity values below this depth approach closely the value of 34.96‰.

STABILITY

The tropospheric waters of Area LIMA, like similar waters in most tropical seas of the world, have a strong positive density gradient of considerable depth. The effect of this density gradient is to prevent the exchange of water in the thermocline with the area's stratospheric water. The stratospheric waters, since no interchange is possible with the surface, have their origin in the arctic and antarctic regions of the Atlantic Ocean.

Since the density of sea water is a function of temperature and salinity, any variation in these factors in a given unit of water will be reflected in a change in the waters density. In June of 1966 the surface water of the part of Area LIMA sampled (Figure 1) was isothermal and approximately isohaline to a depth of 25 meters (Figures 14 and 17). As a result, this same unit of water also displayed an isopycnic (homogenous with respect to density) condition (Figure 18). Similarly the formation and destruction of the seasonal thermocline and halocline will reflect in a like formation and destruction of a pycnocline in the same water. As previously stated, the A water in Area LIMA is effected by seasonal variation to a depth of approximately 150 meters. During June of 1966, the maximum density gradient in this water was found between 25 and 275 meters (Figure 18). In this range the density gradient averaged

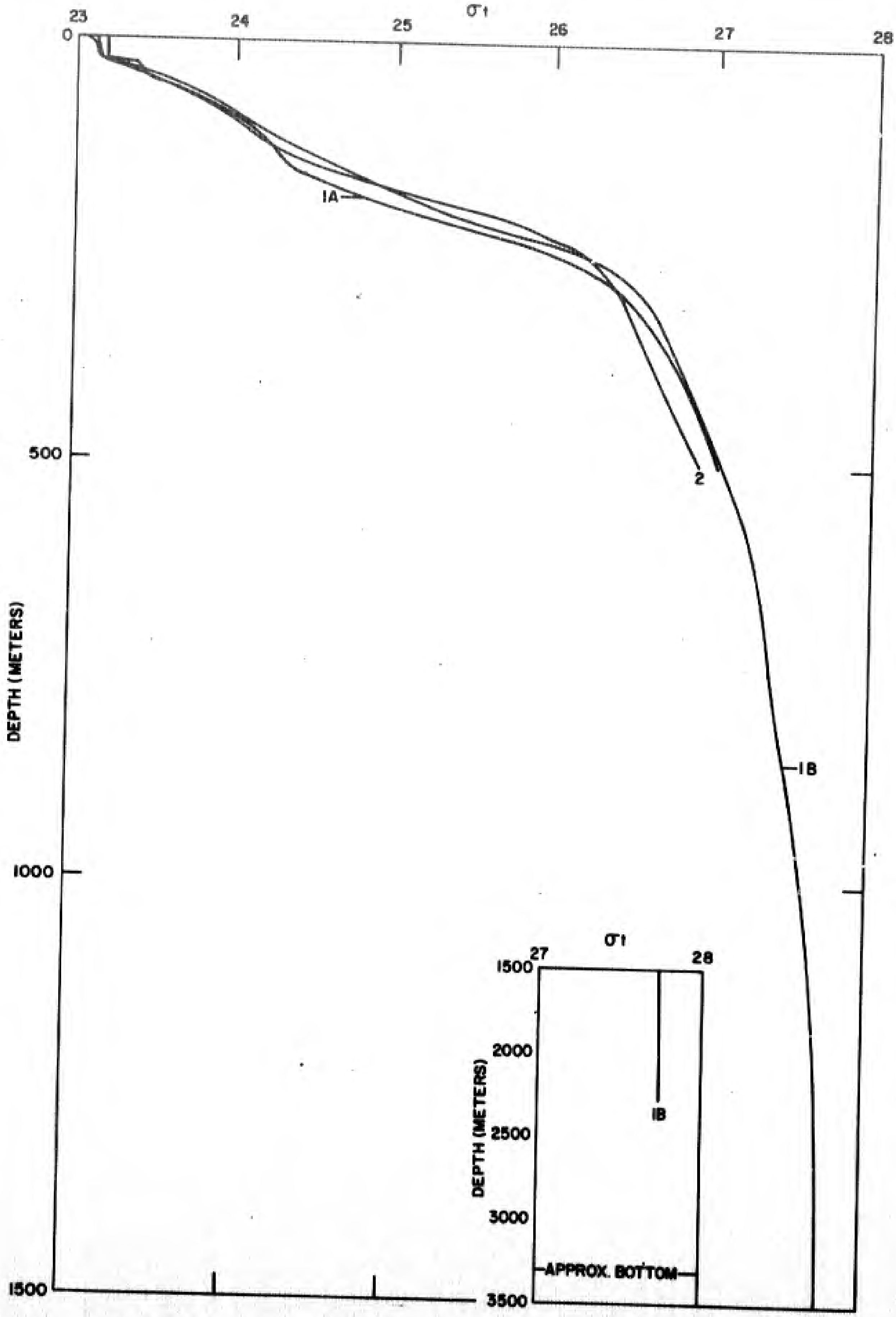

FIGURE 18. COMPOSITE OF DENSITY PROFILES FOR JUNE 1966

$0.128\,\sigma_t/m$. Water residing in this depth range tends to show a minimum of vertical turbulence due to the suppression of vertical water movements by the high density gradient. Comparison of the June 1966 temperature and salinity profiles (Figures 14 and 17) does show a tendency toward reduced vertical variations for temperature and salinity values in the 25 to 275 meter depth range.

Below 275 meters the σ_t gradient decreases $(-d^2\sigma_t/dZ^2)$ down to 1400 meters. Excluding the surface, this is the range that shows the maximum temperature and salinity variation for both the June 1966 data (Figures 14 and 17) and historical data for A water (Figures 11 and 12). Increased temperature and salinity variation at these depths appear to be related to the lessening of the σ_t gradient. The energy source for the above variations is not clear, although internal waves and turbulence related to ocean tides and the Florida Current are suspected.

Below 1400 meters σ_t values for the water are static indicating a water column close to neutral stability. Water at these depths would need only a very small energy input to support turbulence. However, due to the near isothermal and isohaline condition such turbulence cannot be detected by temperature or salinity parameters.

VERTICAL WATER STRATIFICATION

Vertically the water in Area LIMA is a composite of four distinct origins and their zones of mixing. With increasing depths these can be enumerated as Surface Water, Subtropical Underwater, Subantarctic Intermediate Water, and North Atlantic Deep Water.

The depth to which the Surface Water extends is controlled by the greatest depth to which seasonal mixing occurs. In A water the bottom of this layer is marked by a prominent inflection point in both the temperature and salinity profiles. This inflection point occurs at between 100 and 150 meters in the temperature and salinity curves (Figures 11, 12, 14, and 17). Temperature and salinity values in the Surface Water respond to the seasons of the year. These variations were discussed previously. In B water, the depth of the inflection point in temperature and salinity profiles varies between 10 and 125 meters (Figures 11, 12, and 14). The shallowness of the inflection point, in most of the B water, makes it seem improbable that this characteristic is a valid indicator of the bottom of the Surface Water. It is probable that B water does not form a well developed layer of Surface Water, since much of the path of the gyre in which this body of water is located flows

over the continental shelf west of Florida. Mixing and thus destruction of the layer of Surface Water can be expected to occur in the shallow water overlying the continental shelf.

Directly below the bottom of the seasonal thermocline lies a pronounced salinity maximum that marks the presence of Subtropical Underwater (Figures 12 and 17). For the oxygen profile, this water type shows up either as a minimum or a well marked inflection (Figure 13). In A water the core of this water type occurs at a depth of approximately 200 meters. Salinity and temperatures at the core range from 36.60‰ to 36.80‰ and 20.0°C to 22.5°C, respectively. The core depth of the Subtropical Underwater, in B water, appears to be quite variable; ranging between 25 and 150 meters; however, this may be only a reflection of the proximity of some of the sampled B water to the A - B water interface. Subtropical Underwater forms at the surface in the subtropic convergence zones of the North and South Atlantic (Defant, 1961). This water mass flows through the various passes in the Antillean Arc and thence through the Caribbean and Cayman Seas into Area LIMA (Wust, 1964). Though this layer of saline water is quite thin (approximately 100 meters), it suffers comparatively little vertical mixing, due to the presence of a strong density gradient at the depth at which it flows. This gradient tends to suppress most of the vertical turbulence which would normally contribute to the layers destruction (Montgomery, 1938).

The core of Subantarctic Intermediate Water is seen in Area LIMA as a broad salinity minimum located at between 650 and 900 meters (Figures 12 and 17). The core of this water type is approximated by the core of the phosphate maximum and its upper surface is approximated by the intermediate oxygen minimum (Table 2). From salinity profiles of A water, the core of Subantarctic Intermediate Water varied from 775 to 900 meters. The salinity at the core varies from 34.85‰ to 34.88‰ and the temperature from 6.6°C to 7.1°C. In the three salinity profiles of B water, the core depth ranged from 650 to 750 meters. The salinity and temperature values at the core are within the values given for the core in A water. The significant difference between Subantarctic Intermediate Water in A and B water is that the core of the water type in B water is elevated approximately 200 meters above the corresponding core A water.

Subantarctic Intermediate water is formed at the South Atlantic Polar Front (48° - 52°S), (Wust, 1964). From this latitude, it spreads northward below the surface and enters Area LIMA by way of the Cayman Sea. During the passage from the area of formation to Area LIMA, this water type suffers considerable mixing. In Area LIMA, the core of Subantarctic Intermediate

TABLE 2

DEPTH OF SELECTED HYDROGRAPHIC FEATURES

STATION	SALINITY MINIMUM	PHOSPHATE MAXIMUM	OXYGEN MINIMUM
1	750	800	
B	800	800	650
D	850	850	700
E	850	825	650
F	900	950	700
H	775		650
I	875		700
J	875		750
K	750		
L	850		
A	750	750	500
C	650	600	350
G	650		

Water represents less than 5% concentration of the original formation water (Wust, 1964).

North Atlantic Deep Water forms the deep and bottom water of Area LIMA. It appears in the water column in Area LIMA at approximately 1300 meters for A water and 1100 meters for B water. It is in this water mass that A and B water lose their identity (Figures 11 and 12); temperature and salinity values are approximately 4.26°C and 34.98‰, respectively. Oxygen values show considerable variation but average near 4.9 m./L (Figure 13). Worthington (1955) has presented evidence that the oxygen at this level is decreasing at approximately 0.015 ml/L/yr. This reduction is cumulative, since the deep and bottom water is not at present being renewed.

Evidence presented by Worthington (1954) seems to indicate that North Atlantic Deep Water forms periodically along the south coast of Greenland. This water crosses the Antillean Arc into the Cayman Basin and the Gulf of Mexico by way of the Windward Passage. According to Worthington (1955), the bottom water in the Cayman Basin was last renewed in approximately 1840 by overflow of North Atlantic Deep Water through the Windward Passage. The deep water of the Cayman and adjacent Gulf of Mexico has been relatively stagnant since then.

SPEED OF SOUND

In Area LIMA, the decrease in temperature associated with the thermocline causes a rather rapid decrease in sound speed to approximately 700 meters (Figure 19). Below this depth, the sound speed gradient decreases and at about 1000 meters reverses. From approximately 1200 meters to the sea bottom, the water temperature changes very little. This relatively isothermal character of the waters below 1200 meters allows the increase in pressure, with increasing depth, to effect a constant increase in the speed of sound with depth.

The depth of the sound channel axis, which is defined as the depth at which the speed of sound is at its minimum, occurs at approximately 1000 meters (Figure 19). The depth of the sound channel axis can be expected to vary in response to variations in the water's temperature-depth characteristics. These variations will be especially marked between A and B water, with the sound channel axis being considerable shallower in B water.

OXYGEN MINIMUM

Oxygen values are available from nine historical stations in Area LIMA

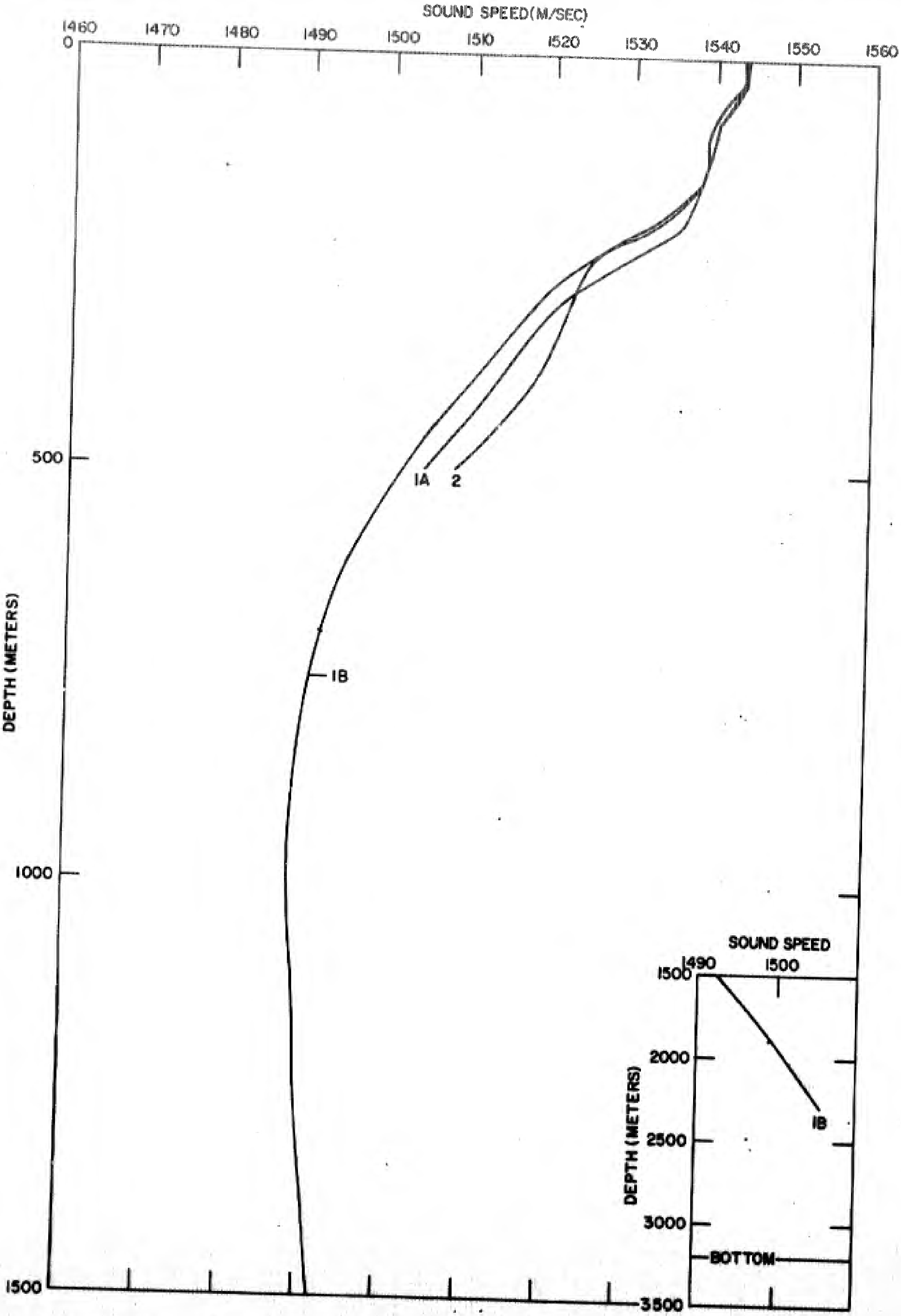

FIGURE 19. COMPOSITE OF SOUND SPEED PROFILES FOR JUNE 1966

and the area immediately adjacent to it (Table 1). Three of these stations were occupied by the ATLANTIS in 1935 and six were occupied by the HILDAGO in 1962. Of the nine sets of data, seven were taken in A water and two were taken in B water.

Since only two stations represent B water, nothing definitive can be said about the oxygen characteristics of this water; however, several general characteristics are apparent from Figure 13. The oxygen minimum in B water appears to be much broader than the minimum found in A water, and the minimun appears to lie higher in the water column.

The oxygen data available for A water, in and adjoining Area LIMA, indicates the oxygen minimum is located between 600 and 800 meters (Table 2). Wust (1964) gave a depth range of from 500 to 800 meters for the oxygen minimun in the general area in which Area LIMA is located. An apparently closer data correlation can be made by comparing the temperature and salinity values corresponding to the depth at which the oxygen minimum is found. Such corresponding values give an average of 8.90°C and 35.03‰ for the data collected by the ATLANTIS and 9.15°C and 35.05‰ for the data collected by the HILDAGO. Wust (1964) gives values of 8° to 9°C and 34.9 to 35.0‰ for the Cayman Sea, through which type A water undoubtedly passes before arriving in Area LIMA. Using the above average temperature and salinity values for the ATLANTIS and HILDAGO station data, the depth of the oxygen minimum for the various stations taken during June 1966 can be estimated. To obtain such an estimate, the June 1966 temperature and salinity values were extrapolated down to 8.9°C and 35.0‰. The extrapolation was accomplished by superimposing the historical temperature and salinity profiles on the respective June 1966 profiles and drawing what appeared to be a reasonable extension on the profiles. Oxygen minimum depth values were then estimated for the three sets of data by plotting the 8.9°C, 9.15°C, 35.03‰, and 35.05‰ values on each set of curves and choosing the exteme maximum and minimum values for each set of data. The estimated depths of the oxygen minimum are shown in Figures 16 and 17. The estimated depth ranges are as follows:

Station	Depth Range
1A	625–650 m
1B	600–675 m
2	675–700 m

These values are well within the previously mentioned depths (500–800 m) given by Wust (1964). Oxygen values at the minimum for both the historical data and Wust's data range from 2.5 to 2.9 ml/L. This large range of oxygen values at the minimum may not be real. Wust, in referring to the analysis of oxygen by the Winkler method, states: "However, Carritt et al., recently

became aware of occasional large systematic errors on some former expeditions (particularly during the IGY period of 1956-58) caused by different procedures used in standardizing the titersolution."

PHOSPHATE

Total phosphate values are lowest at and near the surface (Figure 20). The present and historical data indicates that the low surface concentration of phosphate extends to a depth of between 100 and 150 meters. This is approximately the lower boundary of the Surface Water. Phosphate values in it can be expected to be low and fairly uniform since this layer, at least in A water, is subject to vertical mixing. Below 150 meters, phosphate values increase until a maximum is reached at approximately 800 meters (Figure 20). Phosphate values then decrease slightly with depth, but still maintain relatively high values. The depth at which the phosphate maximum occurs varies considerably even in the same kind of water (Table 2). However, examination of the depths at which the phosphate maximum and the salinity minimum occurs indicates a strong correlation between individual pairs of values.

It seems probable that the phosphate maximum has its source in the South Atlantic and Antarctic Oceans. These waters are relatively rich in phosphate compared to waters of the North Atlantic (Riley, 1951). From this source the water of high phosphate concentration is carried into the Gulf of Mexico as an integral part of the Subantarctic Intermediate Water.

SILICATE

Profiles of silicate concentration obtained during June 1966 in Area LIMA are shown in Figure 21. Of these, only one profile reaches below 500 meters. These few data allow only the most general conclusions.

Silicate concentrations are quite low in the waters from the surface to approximately 200 meters. Below 200 meters silicate concentrations increase, but appear to show a much greater variation in concentration in the 300 to 500 meter range than either phosphate or oxygen. Silicate concentrations up to 28 μ gm $^{at}/L$ form a broad maximum centered at approximately 1400 meters. This is approximately 400 meters deeper than the phosphate maximum and 700 meters deeper than the oxygen minimum. Below 1400 meters silicate values drop off only slowly, the concentration decreasing only 2.8 μ gm $^{at}/L$ in 900 meters.

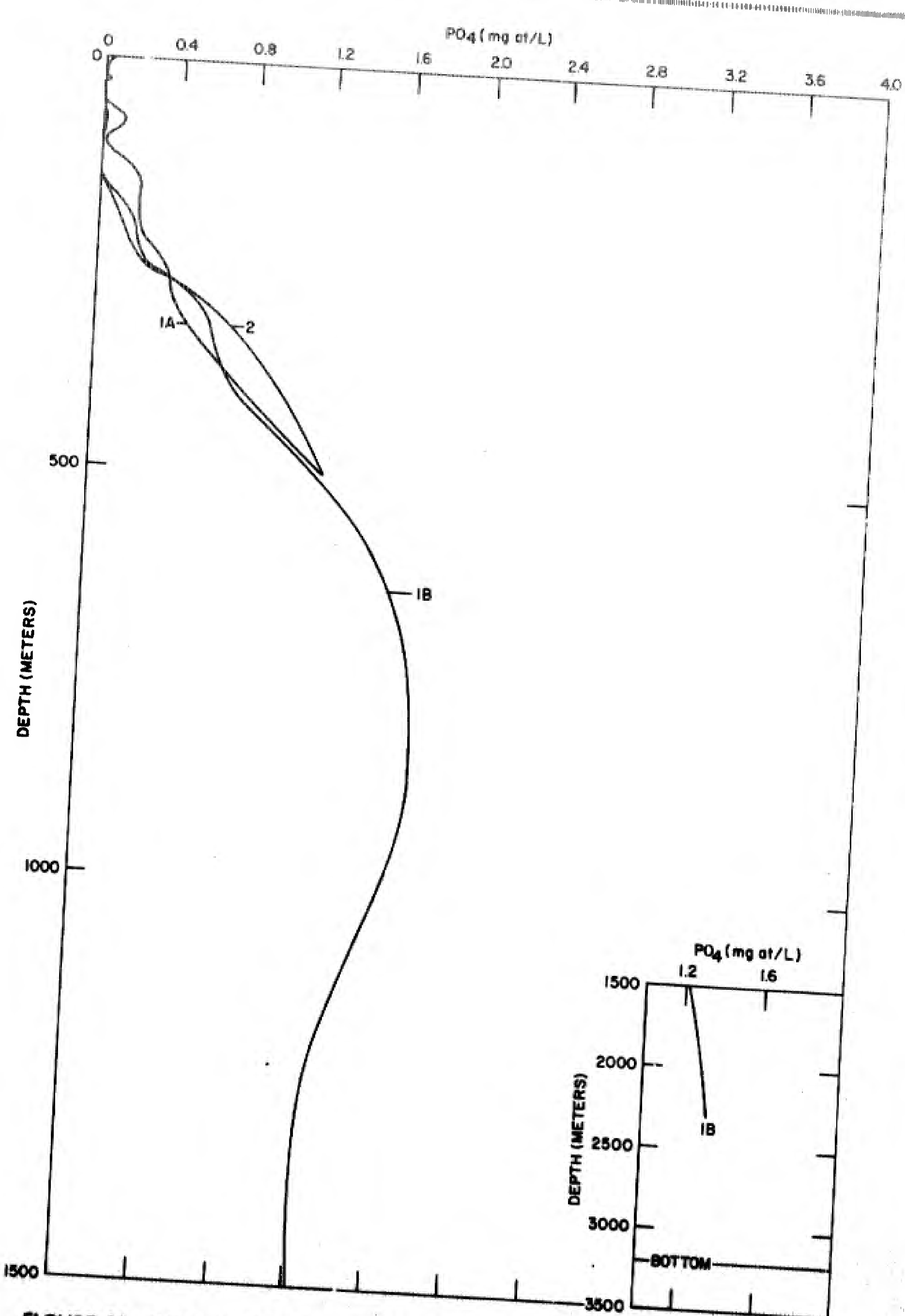

FIGURE 20. COMPOSITE OF INORGANIC PHOSPHATE PROFILES FOR JUNE 1966

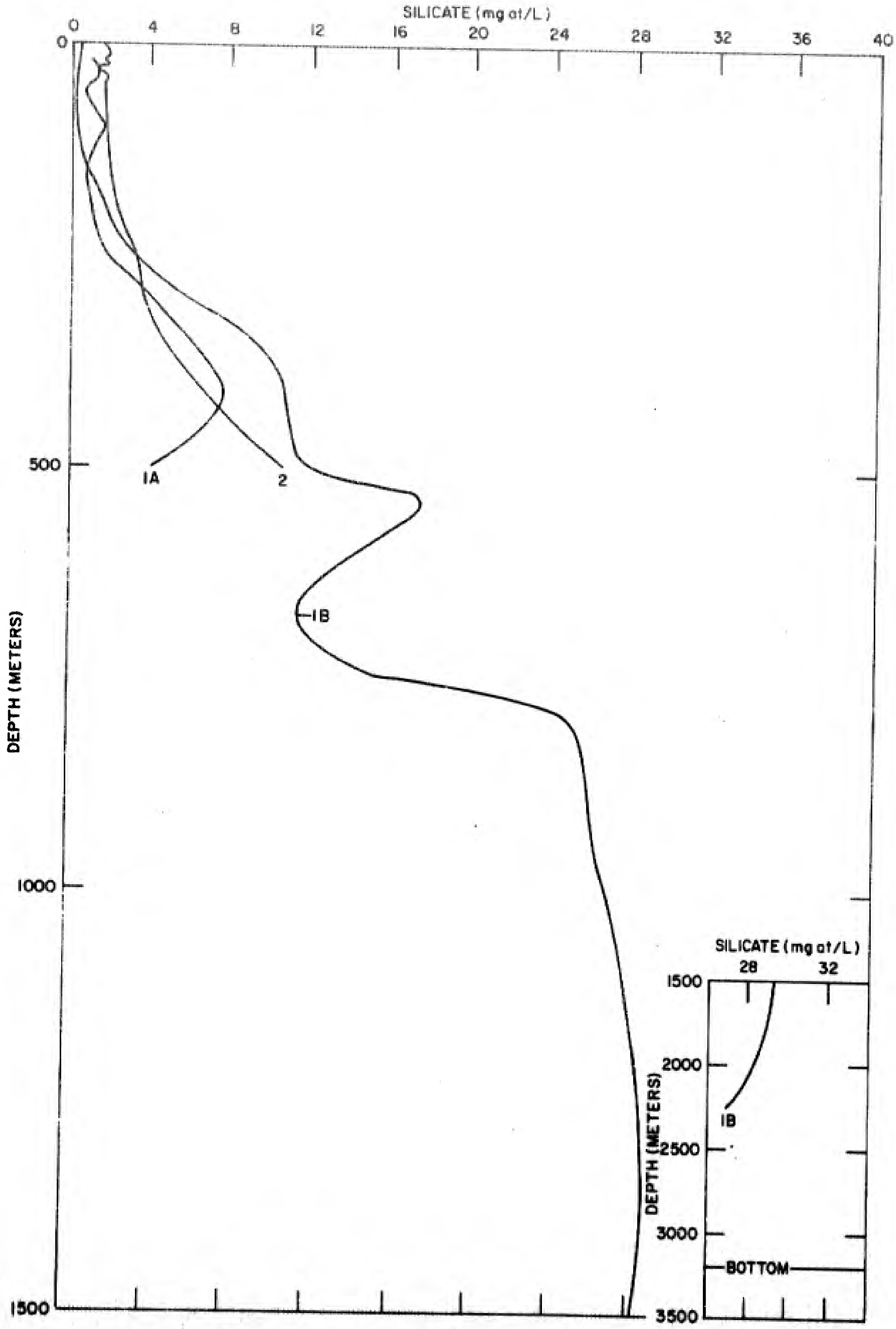

FIGURE 21. COMPOSITE OF SILICATE PROFILES FOR JUNE 1966

CONCLUSIONS

In an attempt to determine exact relationships, acoustic, oceanographic, and biological data were attained with maximum simultaneity. As previously mentioned, the biological data have not been completely processed. Therefore, no mention of this very important facet of the program can be made. As the acoustic data shows, there is very little variation in the scattering strength values and curves obtained from Station 1 and 2. The oceanographic data, in particular the temperature and salinity profiles, also display this similarity. The conclusion is that the two stations of the June cruise were within the same oceanic water mass and hence possessed similar acoustic parameters. This water mass seems to be influenced chiefly by the Florida current. The historical oceanographic data does hint of variations for different seasons, but no correlation with seasonal acoustic and biological data is possible.

Pertaining to the echograms, the only discernible correlation is that the bottom of the seasonal thermocline coincides with the bottom of the shallow non-migratory scattering layer. This may or may not prove significant in future studies of this area. The oxygen, silicate, and phosphate minima and maxima all occurred too deep in the water column to allow correlation with the existing acoustic data.

It is the feeling of the authors that an acoustic technique using pulses of constant frequency (CW), in lieu of explosives, would be a better source of acoustic data for correlation with oceanographic data. At best, with the existing data no definite correlations are found. This is due primarily to three causes; (a) the unavailability of seasonal data for acoustics and biology, (b) the limitations of the explosive technique for measuring scattering strength, i.e., omnidirectionality of the system, time constant of 10^{-4} seconds, etc., and (c) the insignificant oceanographic and acoustic variations from station to station.

APPENDIX A

APPENDIX A

Consider the incremental acoustic intensity received at a hydrophone from an element of insonified volumn dV located at a distance R_1, from the hydrophone;

$$dI(t) = \frac{M(R, \theta, \phi)\, I_1\, dV}{R_1{}^2} \qquad \text{A1}$$

where $M(R, \theta, \phi)$ denotes the volume scattering coefficient of the medium and I_1, the intensity of the incident sound.

It is worthwhile to note here the assumptions upon which the derivation is based.

1. The explosive source is isotropic,
2. A onmidirectional hydrophone is used,
3. Deviations from ideal inverse square spreading loss are neglected,
4. The energy incident upon the scattering volume is reradiated uniformly in all directions in real time (i.e., no time lags),
5. The concentration of scatterers is uniform in any given horizontal plane, and
6. Hydrophone and source are coincident.

We can express the incident intensity I_1 by

$$I_1 = \frac{E}{4\pi R_2^2 \tau}, \qquad \text{A2}$$

where

E represents the total of the energy in the sound source,

τ the period of the shock wave or "pulse" duration, and

R_2 the distance between charge and insonified volume.

Utilizing assumption No. 6, A1 and A2 can be combined to obtain

$$dI(t) = \frac{M(R, \theta, \phi)\, E}{4\pi R^4 \tau}\, dV. \qquad \text{A3}$$

From Figure 22 we obtain, upon conversion to spherical coordinates, the relation

$$dV = R^2 \sin\theta \, d\theta \, d\phi \, dR. \qquad \text{A4}$$

Substitution into equation A3 yields

$$dI(t) = \frac{M(R, \theta, \phi)\, E}{4 \pi R^2 \tau} \sin\theta \, d\theta \, d\phi \, dR. \qquad \text{A5}$$

Substitution of $R = \frac{Ct}{2}$, and $dR = \frac{C\tau}{2}$

into equation A5 and integrating we obtain after simplification

$$I(t) = \frac{1}{2 \pi C t^2} \int_0^{2\pi} \int_0^{\pi/2} M(R, \theta, \phi)\, E \sin\theta \, d\theta \, d\phi\,. \qquad \text{A6}$$

where t is time after detonation (seconds), and C is the speed of sound in sea water in yds/sec.

From the fifth assumption pertaining to the distribution of scatterers, the scattering coefficient $M(R, \theta, \phi)$ becomes a function of depth only.

Integrating with respect to ϕ and then changing from the θ limits to depth z limits yields

$$I(t) = \frac{2E}{C^2 t^3} \int_0^z M(z)dz. \qquad \text{A7}$$

Using the relation for intensity

$$I(t) = \frac{\left[P(t)\right]^2}{\rho c}, \qquad \text{A8}$$

where ρc is the familiar acoustic impedance, and P(t) is pressure in dynes/cm^2, we can convert equation A7 into a usable form by solving for a scattering coefficient for the entire depth z.

$$\int_0^z M(z)dz = \frac{C^2 t^3 \left[P(t)\right]^2}{2E \rho c} \qquad \text{A9}$$

Since the energy contribution of the bubble pulses is negligible compared to the

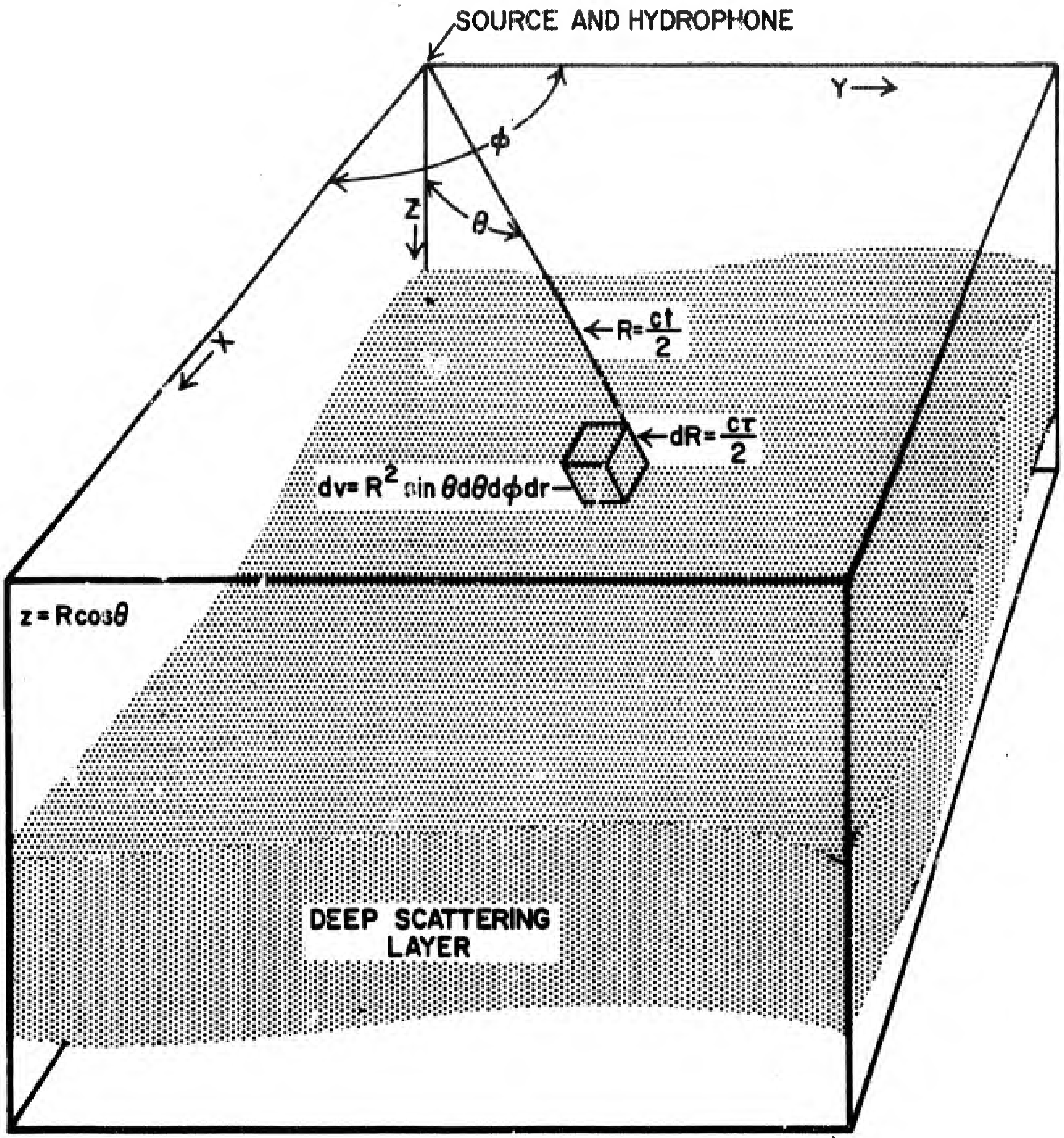

FIGURE 22. GEOMETRY FOR SCATTERING STRENGTH DERIVATION

shock wave for our range of frequencies we need consider only the pressure P'(t) of the shock wave represented by

$$P'(t) = \begin{cases} P_o e^{-t/\alpha} & t > 0 \\ 0 & t < 0 \end{cases} \qquad \text{A10}$$

where P_o is the peak pressure and α is the time constant of the shock wave. Using equations for evaluating P_o and α from Arons and Wertheim (1950), we obtain for a 2 pound charge of TNT the values

$$\alpha = 58\,(10^{-6})\,W^{1/3}\left(\frac{W^{1/3}}{R}\right)^{-.22} \approx 10^{-4}\ \text{sec} \qquad \text{A11}$$

and $$P_o = 2.16\,(10^4)\left(\frac{W^{1/3}}{R}\right)^{+1.13} \approx 8.03 \times 10^3\ \text{lbs/in}^2. \qquad \text{A12}$$

Where

W = charge weight in lbs,

R = radial distance from explosion in ft.,

α = time constant in seconds, and

P_o = initial peak pressure in lbs/in^2

We may convert equation A10 from the pressure domain to the frequency domain by use of a Fourier integral

$$P'(t) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} g(\omega) e^{-i\omega t}\, d\omega, \qquad \text{A13}$$

where

$$g(\omega) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} P(\tau) e^{-i\omega\tau}\, d\tau. \qquad \text{A14}$$

Combining A10 and A14 yields

$$g(\omega) = P_o\,(2\pi)^{-1/2}\,(1/\alpha + i\omega)^{-1}. \qquad \text{A15}$$

Taking the absolute magnitude of A15 by the method of complex conjugates yields

$$\left| g(\omega) \right| = \frac{P_o}{(2\pi)^{1/2}} \quad \frac{1}{[\alpha^{-2} + \omega^2]^{1/2}}, \qquad \text{A16}$$

where ω represents the angular frequency $2\pi f$.

The total energy flux of the explosive shock wave can be expressed by

$$E = (\rho c)^{-1} \int_{-\infty}^{\infty} [P(t)]^2 \, dt, \qquad \text{A17}$$

By using Plancherel's theorem:

$$E = (\rho c)^{-1} \int_{-\infty}^{\infty} \left| g(\omega) \right|^2 \, d\omega, \qquad \text{A18}$$

we obtain

$$E = \frac{P_o^2}{2\pi\rho c} \int_{-\infty}^{\infty} \frac{d\omega}{\alpha^{-2} + \omega^2}. \qquad \text{A19}$$

To convert from energy flux to total energy radiated in all directions, it is necessary to multiply equation A19 by 4π to give

$$E = \frac{2 P_o^2}{\rho c} \int_{-\infty}^{\infty} \frac{d\omega}{\alpha^{-2} + \omega^2} = \frac{2 P_o^2}{\rho c} \left[\int_{\omega_1}^{\omega_2} \frac{d\omega}{\alpha^{-2} + \omega^2} + \int_{-\omega_1}^{-\omega_2} \frac{d\omega}{\alpha^{-2} + \omega^2} \right]. \qquad \text{A20}$$

It is pertinent to mention that equation A20 contains energy associated with negative as well as positive frequencies.

Performing the above integration yields

$$E = \frac{4 P_o^2 \alpha}{\rho c} \tan^{-1} \frac{2\pi \alpha (f_2 - f_1)}{1 + 4\pi^2 \alpha^2 f_2 f_1}. \qquad \text{A21}$$

Substituting this expression in equation A9 gives

$$\int_0^z M(z) dz = \frac{c^2 t^3 [P(t)]^2}{8 P_o^2 \alpha} \left(\tan^{-1} \left[\frac{2\pi \alpha (f_2 - f_1)}{1 + 4\pi^2 \alpha^2 f_2 f_1} \right] \right)^{-1}, \qquad \text{A22}$$

Converting to the more useful logarithmic form

$$10 \log \int_0^z M(z)dz = 20 \log c + 30 \log t + 20 \log P(t)$$

$$-10 \log 8 - 20 \log P_o - 10 \log \alpha$$

$$-10 \log \tan^{-1} \left[\frac{2\pi \alpha \; (f_2 - f_1)}{1 + 4\pi^2 \alpha^2 f_2 f_1}\right]. \qquad \text{A23}$$

Combining known constants and subtracting 6 dB due to contributions from the surface reflected paths gives the final form

$$10 \log \int_0^z M(z)dz = 20 \log P(t) + 30 \log t$$

$$-10 \log \tan^{-1} \left[\frac{2\pi \alpha \; (f_2 - f_1)}{1 + 4\pi^2 \alpha^2}\right] \quad -86 \qquad \text{A24}$$

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13. ABSTRACT

Volume reverberation data from the deep scattering layer and oceanographic data, for June 1966, are presented for an area located in the Gulf of Mexico. Volume scattering strength values are presented for one-third octave bands between 2.5 kHz and 20 kHz. Values of scattering strength range from a minimum of -69db at 2.5 kHz to a maximum of -48 db at 5 kHz. Diurnal variations of scattering strength with frequency are shown; the values decreasing with increasing frequency. Echo sounder records of scattering layers resonant at 12 kHz are examined for one station and the apparent migration rates and layer thicknesses discussed.

Oceanographic data, collected coincident with the acoustic data, indicate that the area under investigation is located within Florida Current water. Historical oceanographic data shows that water laying off the west coast of Florida forms a boundary with the Florida current water and that this boundary zone can be expected to approach or transverse the area occasionally. Both the collected acoustic and oceanographic data show little variation from location to location.

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A VOLUME SCATTERING AND OCEANOGRAPHIC STUDY OF AN AREA IN THE EASTERN GULF OF MEXICO						

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